David Fernández

Development of the calibration and limit checking modules for a satellite's ground control software

Aalto Universiy School of Electrical Engineering

Department of Radio Science and Engineering

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Thesis supervisor and instructor: D.Sc. (Tech.) Jaan Praks

Aalto University
School of Electrical
Engineering

Aalto University
School of Electrical Engineering

Abstract of the
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The goal of this project is to develop the calibration and limit checking modules for Hummingbird, an open source software platform for controlling ground stations and satellites which is being developed by CGI Group Inc. in co-operation with the University of Tartu. Hummingbird is presented in detail and its architecture, functionalities and core technologies are described in the work.

The work also gives a short overview of the topics which are most relevant to satellite communications. Such as orbits, communication protocols, the ground segment and ground segment software solutions.

The software design made in this work was developed in close cooperation with the scientists working on the Estonian student satellite. The result is a completely configurable software prepared to be fully integrated with Hummingbird when necessary.

Keywords: nanosatellite, ground station, calibration, limits, communications, orbits, Hummingbird

All our dreams can come true, if we have the courage to pursue them.

Walt Disney

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Preface

Before I started this thesis, my knowledge about space technology was close to zero. Nevertheless, when I was told about the possibility of working in the project of building the first satellite that Finland will launch into space, I did not hesitate for a second. Working in the project was great opportunity and I had to take it.

My work has been done at the Department of Radio Science and Engineering of Aalto University and my main goal has been to produce software for the ground segment of the mission. It has been really challenging, but it has also given me the chance to gain knowledge in several space related areas which some months ago where somehow like magic for me.

It has been real pleasure being a small part of this project. I believe these satellites are the present and future for universities, and they can help students see that all the effort they put during their studies can accomplish something as amazing as putting their own satellite into orbit.

Acknowledgements

I cannot start in any other way than thanking my parents, Manuel and María del Carmen. Without you this would not be happening, thank you for your constant love and trust. Thank you for everything you have taught me and keep teaching me everyday. Also, thank you for your great support when I decided to move abroad. I love you.

Thanks to Aalto University, especially to Jaan Praks, who invited me to participate in the great adventure that is Aalto-1 and has supervised my thesis. Also, many thanks to the Aalto-1 team. It has been great working with you.

Many thanks to Urmas Kvell and the ESTCube team. Thank you for your cooperation during my visits to Estonia and also for your invitation to stay at the Tõravere Observatory for two weeks. My stay there was very fruitful and interesting.

I would also like to thank Gonzalo Mariscal, International Manager of the School of Engineering at Universidad Europea de Madrid. Thank you for your support during these two years and also for all the times I bothered you with questions before I moved to Finland.

Finally, I want to say thanks to all the friends who have helped me since I came to the country; especially to Adrián Yanes, who convinced me to come to Finland in the first place and has been a great friend for the last eight years. Also to Borja Tarrasó, whose support and friendship since I arrived have been very important to me. You guys have always been there, thanks. I do not want to forget Alberto Alonso, one of the last additions to our group whom has proved to be a great friend. Last, but not least, I want to thank Tuomo Ryynänen and his family. You have made me feel very welcomed in your country. I hope that, in the future, I will be able to reciprocate in mine.

Otaniemi, Espoo, August 2013.

David.

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Symbols and Acronyms

Symbols

a	Semimajor axis
e	Eccentricity
i	Inclination
Ω	Right ascension of the ascending node
ω	Argument of the perigee
v	True anomaly

Acronyms

Aalto-1	First nano-satellite being built by Aalto University (Espoo, Finland)
AX.25	Data link layer protocol
COE	Classical Orbital Elements
CubeSat	Standard for nanosatellites
ESA	European Space Agency
E-sail	Electric Solar Wind Sail
ESTCube-1	First Estonian satellite
Explorer 1	First artificial satellite launched by the United States
FMI	Finnish Meteorological Institute
GUI	Graphical User Interface
GENSO	Global Education Network for Satellite Operations
GS	Ground Station
GSO	Geosynchronous Orbit
HEO	High Earth Orbit
Hummingbird	Open source platform for monitoring and controlling remote assets
Inmarsat-4	Communications satellite operated the satellite operator Inmarsat
ISS	International Space Station
JMS	Java Message Service
JRE	Java Runtime Environment
JVM	Java Virtual Machine
LEO	Low Earth Orbit
MaSat-1	First Hungarian satellite
MEO	Medium Earth Orbit
NaN	Not a Number
NASA	National Aeronautics and Space Administration
NORAD	North American Aerospace Defense Command
OpenGL	Open Graphics Library
OSI	Open Systems Interconnection
OSGI	Open Services Gateway Initiative
RADMON	Radiation Monitor, payload of Aalto-1
Sputnik 1	First artificial satellite launched by the Soviet Union
TLE	Two-Line Elements
UHF	Ultra High Frequency
VHF	Very High Frequency
XML	Extensible Markup Language

Chapter 1

Introduction

The relationship between human beings and space has existed since the beginning of time. Space has always been a source of mystery, something we want to understand. More than 4000 years ago, based on the movements of the Sun and the planets, the Egyptians and the Babylonians developed calendars for growing their crops. Later, the ancient Greeks introduced the concept of *astronomy*, the science of the heavens. Other examples are philosophers such as Nicolaus Copernicus, Johannes Kepler, who explained the motion of the planets, and Galileo Galilei, who has been called the "father of modern observational astronomy" [1]. In the 17th century, Sir Isaac Newton invented calculus, developed his law of gravitation and performed important experiments in optics.

The technological advancements of the 20th century, specially accelerated by the World War II, made physical exploration of space become possible. This exploration is mainly carried out by the use of satellites. A *satellite* is a natural or artificial object moving around a celestial body. This motion is described as an orbit, defined by the dominant force of gravity from the bigger body. In early 1945, the United States started the Vanguard Rocket development to launch a satellite. However, after several failed launches, it was the Soviet Union who took the advantage by launching the Sputnik-1 (Figure 1.1) on October 4, 1957. Finally, on January 31, 1958 the United States managed to launch their first artificial satellite, the Explorer-1 (Figure 1.2). During the Cold War, the space race between the two superpowers was a hard fight which made space technology advance quite rapidly.

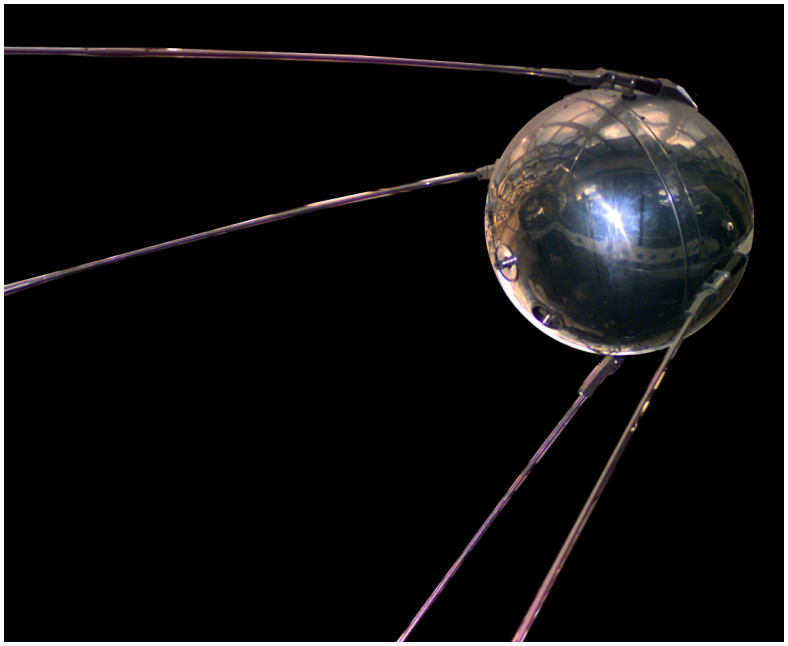


Figure 1.1: Sputnik 1, first artificial satellite launched by the Soviet Union in 1957 (National Aeronautics and Space Administration - Public Domain)

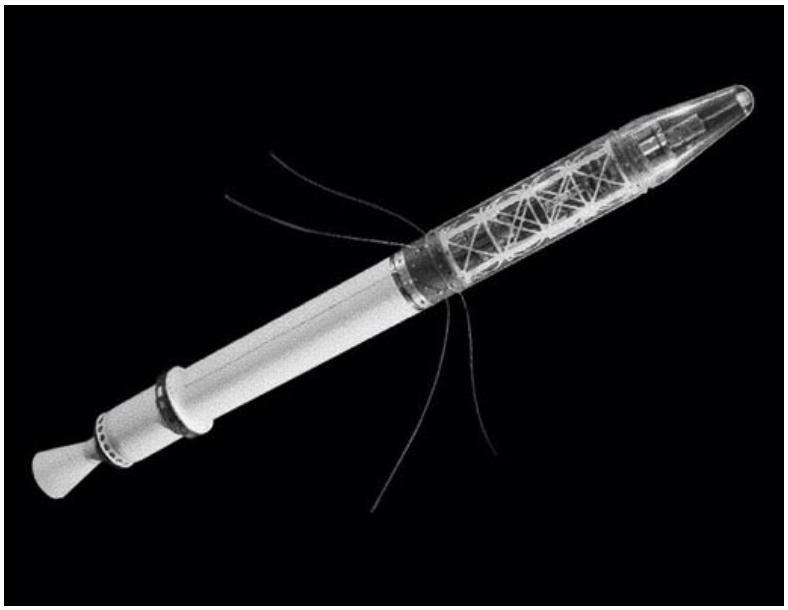


Figure 1.2: Explorer 1, first artificial satellite launched by the United States in 1958 (National Aeronautics and Space Administration - Public Domain)

As of October 1, 2011 there were 966 operating satellites in orbit. About two-thirds of these were owned by the United States, Russia and China [2]. The satellites can be divided into four main categories according to their usage:

- Communications satellites: used for television, radio, Internet and telephone services.
- Navigation satellites: using radio time signals, these satellites allow mobile receivers on the ground to determine their exact position. They are also used to determine the location of satellites situated in lower orbits.
- Exploration satellites: used to observe distant planets, galaxies and other outer space objects by using telescopes and other sensors.
- Remote sensing satellites: Remote sensing satellites are used to gather information about the nature and condition of Earth. The sensors in this kind of satellites receive electromagnetic emissions in several spectral bands and can detect, amongst others, the object's composition and temperature, environmental conditions. This type of satellites have sometimes also been used for military surveillance.

The constant evolution of technology and the growth of human needs have made the complexity and size of the satellites grow throughout the last decades. Satellite mass has grown from Sputnik's 84 kg and Explorer-1's 14k kg to Inmarsat-4's almost 6,000 kg in 2008 [3]. The main consequence of this, amongst others, has been an increment in mission costs.

To counter this trend, the small satellite movement was created by the academic community and it has shown how mission costs can be cut dramatically to a point in which a university can build and launch their own satellite. (Figure 1.3). The success of this concept has created a vigorous industry. Aalto University's student satellite Aalto-1 and Estonian student satellite ESTCube-1, projects with which this thesis is related to, are nanosatellites, and the perfect example of this new trend.

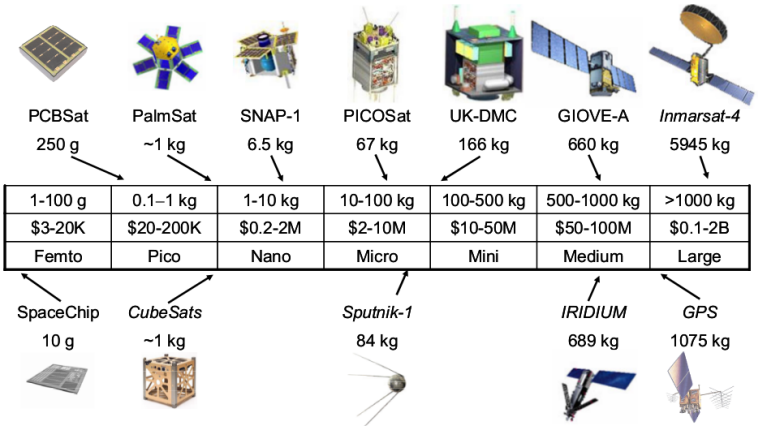


Figure 1.3: Satellite Mass and Cost Classification [3]

1.1 Background

This thesis is closely related to two different university based nanosatellite projects, Aalto-1 and ESTCube-1. These two projects are based on the most common standard used by university satellites: CubeSat [4], an open standard developed by the California Polytechnic State University and Stanford University.

1.1.1 Aalto-1

Led by Aalto University, Aalto-1 project aims to build a multi-payload remote sensing nanosatellite (Figure 1.4). The size of the satellite is approximately 34 cm x 10 cm x 10 cm with a mass of less than 4 kg [5]. Aalto-1 also intents to be the first Finnish satellite.

Figure 1.4: Artist's view of the Aalto-1 satellite

There are different institutions cooperating to make this possible. The main payload, the imaging spectrometer, has been designed and built by VTT Technical Research Centre of Finland. The Radiation Monitor (RADMON) has been designed by the Universities of Helsinki and Turku in cooperation with the Finnish Meteorological Institute (FMI). The Plasma Brake has been designed by a consortium including the FMI, the Department of Physics of the University of Helsinki, the Departments of Physics and Astronomy and Information Technology of the University of Turku, the Accelerator laboratory of the University of Jyväskylä, Aboa Space Resarch Oy, Oxford Instruments Oy and other Finnish companies. Meanwhile, Aalto University is responsible for designing and building the satellite platform and the day-to-day operation of the project. [6]

Aalto-1's mission is to demonstrate the technologies of the payloads in space environment and measure their performance. In addition, it is also an educational project. Students are the main workforce towards its success. Being the the first Finnish student satellite mission, is a good tool to improve Finnish space teaching and also allow students to be in touch with prominent partners, both domestic and international, in the space technology field.

1.1.2 ESTCube-1

ESTCube-1 is a single-unit CubeSat (Figure 1.5). The size of the satellite is approximately 10 cm x 10 cm x 10 cm with a maximum mass of 1.33 kg. It has been built by students of the universities of Tartu and Tallinn, in Estonia, and it is the first Estonian satellite [8]. It was launched from the Guaiana Space Centre on May 7, 2013 as one of the three payloads of the Vega VV02 rocket [9].

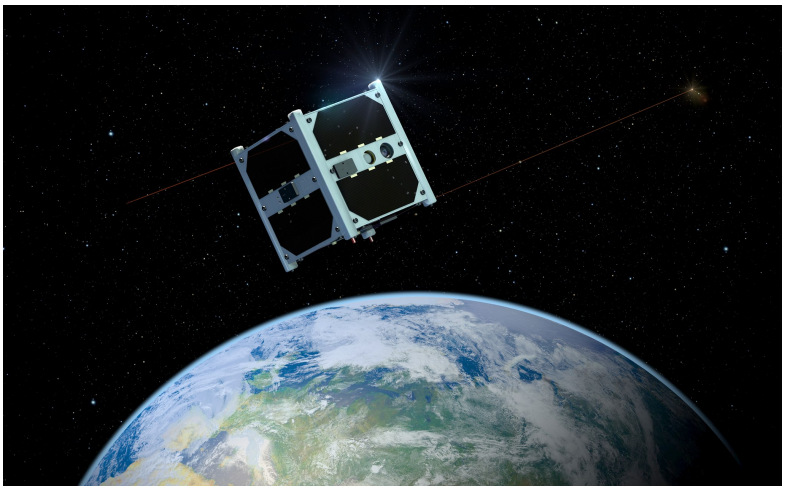


Figure 1.5: Artist's view of the ESTCube-1 satellite

ESTCube-1's main goal is to observe and measure the E-sail [7] effect for the first time. It has been placed into a polar low Earth orbit (LEO) and will deploy a single 10 m long and 9 mm wide tether [8]. This is related to Aalto-1's Plasma Brake, which will deploy a 100 m long tether. The required duration of ESTCube-1's mission is a few weeks and it can be extended to about a year.

1.2 Problem statement

Any satellite mission is divided in two segments:

- Space segment: the satellite.
- Ground segment: this segment provides the means and resources to manage and control the data produced by the diverse instruments [10].

The main part of the groud segment is the ground station. It is the first and final point of communication with the satellite, the place where the data is received and where the satellite is controlled from.

One of the main tasks of any mission is analysing the information received from its several sensors. However, the values generated by the sensors are not usually valid for scientific use as they are received, they are digital values which are not presented in any particular units and need to be calibrated.

The calibration process generates useful scientific values from those generated by the sensors. The equations to do so are provided by the vendors or calculated by experimentation before the launch. One of the main reasons for calibrating the values once they have been received by the ground station is saving downlink bandwidth. For example, a parameter C can be calculated based on the values of A and B, so it makes no sense to calculate it on board and waste downlink bandwidth to send C, when it can be done on the ground. In addition, the calibration equations might change over time, and it is much simpler to change something on the ground segment software than on the satellite.

The received values also need to be checked to see if they are within the specified limits. This allows scientists to discard invalid values or see how healthy the systems in the satellite are. These comparisons will generate several responses in the ground software, so again it only makes sense to do it on the ground.

1.3 Research objectives and scope

The purpose of this thesis is to develop the calibration and limit checking modules for a ground control software which will solve the problems mentioned earlier.

Using ESTCube-1 project as a baseline, the author aims to develop such systems which are generic enough to be used by any number of satellite missions. The modules developed will be integrated into *Hummingbird*, an open source platform for monitoring and controlling remote assets, which will be explained later in this work.

The following items support this purpose:

- Research about satellite orbits and how they affect satellite-Earth communications.
- Research about what types data are exchanged between satellites and ground stations.
- See what are the different parts of a ground station, including hardware and software pieces.
- Present the most common protocols used for amateur satellite communications.

1.4 Motivations

When the moment came to choose a software solution for Aalto-1's ground station, the approach was to develop something ad-hoc for the mission. There was no available software which was good enough for the mission's requirements unless it was oriented for big professional satellites. However, due to the cooperation with the University of Tartu, *Hummingbird* came into play as a real strong option. It is an open source project which, in addition to controlling the ground station and satellite, also aims to create a network of ground stations around the world.

The development of this product will not only benefit both, Aalto University and the University of Tartu. Being open source, any mission can have a ready-to-use, fully tested software as a baseline for their ground control systems, which will help small satellite missions shorten their development time frames.

1.5 Outline of the thesis

This thesis is structured as follows: the second chapter gives a general overview about satellite communications, how orbits affect them, what data is transmitted, what the different protocols are and which hardware and software components are used to carry out those communications. The third chapter explains briefly what Hummingbird is and what is behind it. The fourth chapter goes through the requirements set for the software project whereas the fifth one focuses on the design and implementation. Chapter six comprises a short user manual. Chapter seven summarizes the conclusions of this thesis. Finally, chapter eight explains what the next steps in the project are.

Chapter 2

Satellite Communications

In order to understand how the satellites communicate with Earth, the very basics of satellite communications are covered in this chapter. The first section describes what orbits are, how they are described and how that information can be delivered by a computer. Afterwards, the types of different data exchanged by the satellite and the ground station will be covered. The last section of the chapter presents what a ground station is, its hardware and software components and how it communicates with a satellite in space.

2.1 Orbits

An orbit is the **gravitationally curved path of an object around a center of mass**. Examples of orbits can be the Earth around the Sun or artificial satellites around the Earth.

2.1.1 Kepler's Laws

Planetary movements were first mathematically defined by the German mathematician, astronomer and astrologer Johannes Kepler in the 17th century. He concentrated his observations into three simple laws [11]:

- The orbit of each planet is an ellipse with the Sun occupying one focus.
- The line joining the Sun to a planet sweeps out equal areas in equal intervals of time.
- A planet's orbital period is proportional to the mean distance between the Sun and the planet, raised to the power of 3/2.

These laws generally apply to every celestial body. When analysing the movement of two bodies, if one is much bigger than the other, an approximation known as

the two-body problem can be used. It assumes that both bodies are spherical and they are modelled as if they were point particles. This means that influences from any third body are discarded. The solution of the two-body problem states that the smaller body orbits around the bigger one in an elliptical orbit which can be described by six parameters. These parameters will be explained in detail in the next section.

2.1.2 Classical Orbital Elements

The Classical Orbital Elements (COEs) are six parameters which uniquely define the orbit and location of the body. They also can be used to predict future positions of the satellite. [12]

The first two elements, the orbit's size and shape are defined based on a 2D representation on an ellipse (Figure 2.1).

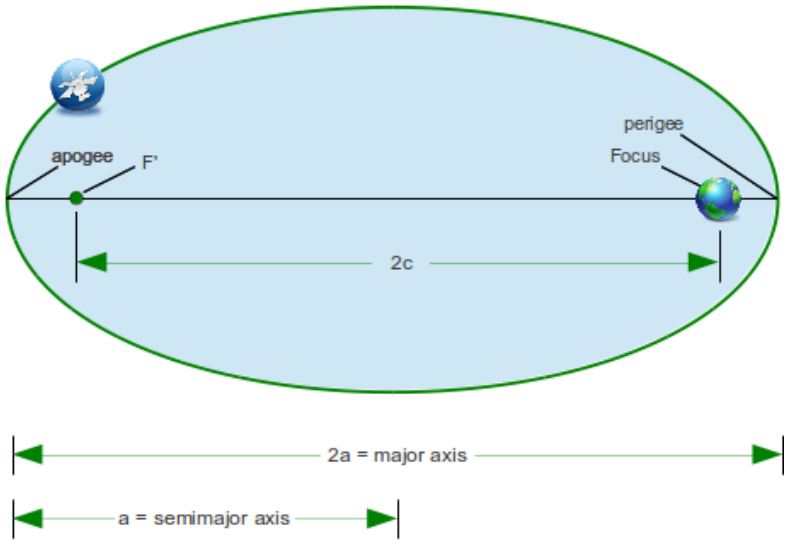


Figure 2.1: Semimajor axis on an ellipse

- The *semimajor axis* (a) is one half the distance across the long axis of the orbit, and it represents the orbit's size.
- The *eccentricity* (e) represents the shape of the orbit. It describes how much the ellipse is elongated compared to a circle. Based on the latter, the orbit can have different shapes, as shown in Figure 2.2.

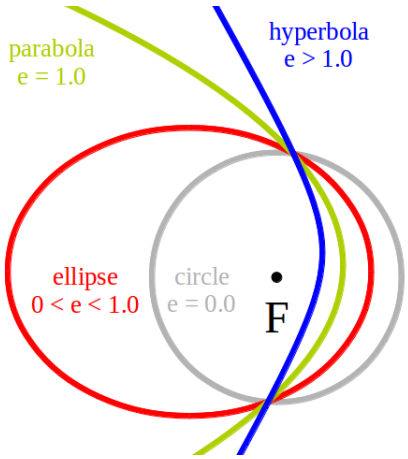


Figure 2.2: Shapes of an orbit based on its eccentricity

Before jumping onto the next orbital elements it is necessary to point out that the Geocentric-equatorial coordinate system will be used. It is now a 3D representation, where the reference plane is Earth's equatorial plane and the principal direction is in the vernal equinox direction (see Figure 2.3).

The following orbital elements define the orientation of the orbital plane:

- The inclination (i) describes the tilt of the orbital plane with respect to the reference plane. It is measured at the ascending node. This is, where the orbit crosses with the reference plane when moving upwards.
- The right ascension of the ascending node (Ω) represents the angle between the principal direction and the point where the orbital plane crosses the reference plane from south to north measured eastward.

It is now time to go through the last two COEs:

- The argument of perigee (ω) is the angle between the ascending node and the perigee, measured in the direction of the satellite's motion.
- The true anomaly (υ) specifies the location of the satellite within the orbit. Amongst all the COEs, this is the only one which changes over time. It is the angle between the perigee and the satellite's position vector measured in the direction of its motion.

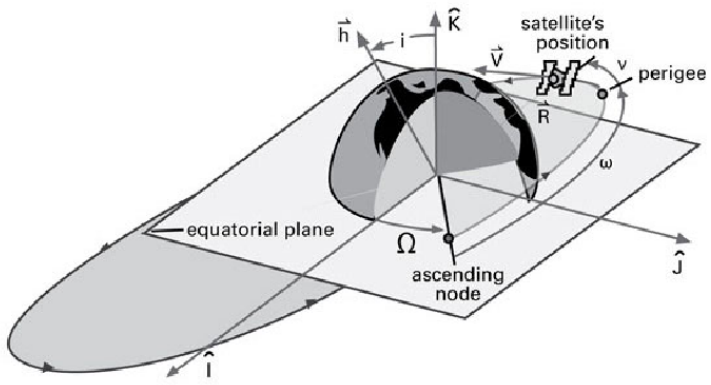


Figure 2.3: Classical Orbital Elements [12]

Based on the COEs, the orbits can be classified as shown in Table 2.1.

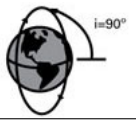
Inclination (i)	**Orbital Type**	**Diagram**
0° or 180°	Equatorial	
90°	Polar	
$0° \leq i < 90°$	Direct or Prograde (moves in the direction of Earth's rotation)	
$90° < i \leq 180°$	Indirect or Retrograde (moves against the direction of Earth's rotation)	

Table 2.1: Types of orbits and their inclination [12]

Although it is not part of the COEs, orbits can also be sorted by their altitude. NASA's classification divides orbits in three groups (Table 2.2).

Orbit	**Altitude (a)**	**Uses**
Low Earth Orbit (LEO)	$a < 2000Km$	Scientific and weather satellites
Medium Earth Orbit (MEO)	$2000Km \leq a < 36000Km$	GPS
High Earth Orbit (HEO) or Geosynchronous (GSO)	$36000Km$	Communications (phones, television, radio)

Table 2.2: NASA's classification of orbits [13]

2.1.3 Ground Tracks

The satellite ground tracks are the projection of its orbit onto Earth, they are used to clearly explain how the satellites move in reference to an observer on the ground. An example of this can be Figure 2.4.

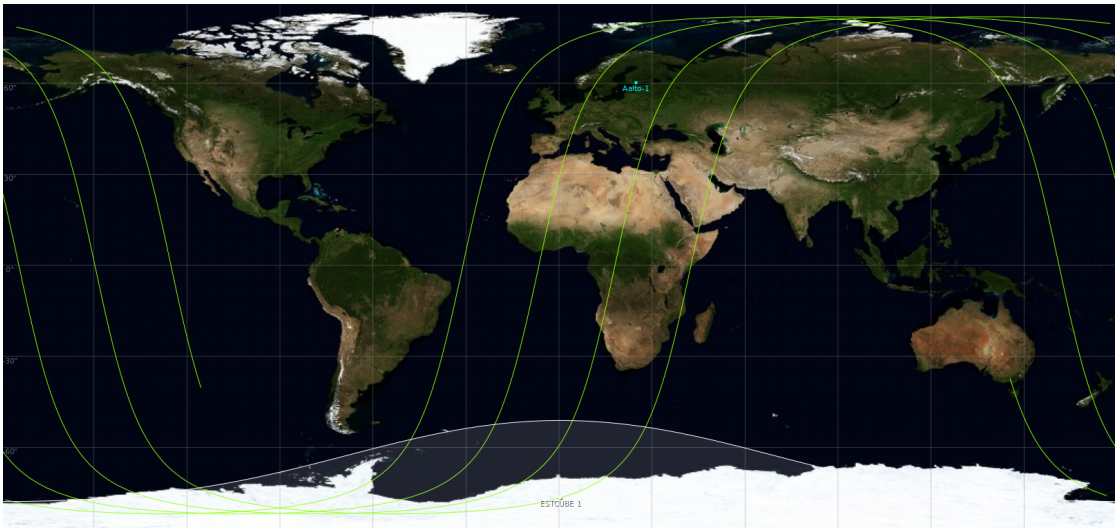


Figure 2.4: Ground Tracks of ESTCube-1

In an ideal two-body solution and if Earth did not rotate, the representation of a satellite's orbit would be a single line, as the ground track would continuously repeat. However, Earth rotates at 1600 km/hr. Thus, even if the orbit does not change, from the Earth-based observer's point of view it appears to shift to the west.

This poses a challenge to the communication with the satellite. It is visible, as a fast moving object in the sky, from a certain location on the ground for very short

periods of time. Thus, the communications antenna needs to track the satellite in order to handle the communication. The tracking is based on two-line element sets, which will be covered in the next section.

2.1.4 Two-Line Elements

A Two-Line Element (TLE) set is a data format created by the North American Aerospace Defense Command (NORAD) and NASA to transport sets of orbital elements describing satellite orbits around Earth. These TLEs can be later processed by a computer to calculate the position of a satellite at a particular time and are usually used by ground stations in order to track them.

The following snippet shows an example of a TLE for the International Space Station. The meaning of its different parts is explained in Tables 2.3 and 2.4.

```
ISS (ZARYA)
1 25544U 98067A 13166.62319444 .00005748 00000-0 10556-3 0 120
2 25544 51.6483 116.0964 0010829 73.3727 265.7013 15.50799671834453
```

Field	Columns	Content	Example
1	01	Line number	1
2	03-07	Satellite number	25544
3	08	Classification (U=Unclassified)	U
4	10-11	International Designator (Last two digits of launch year)	98
5	12-14	International Designator (Launch number of the year)	067
6	15-17	International Designator (Piece of the launch)	A
7	19-20	Epoch Year (Last two digits of year)	08
8	21-32	Epoch (Day of the year and fractional portion of the day)	264.51782528
9	34-43	First Time Derivative of the Mean Motion	-0.00002182
10	45-52	Second Time Derivative of Mean Motion (decimal point assumed)	00000-0
11	54-61	BSTAR drag term (decimal point assumed)	-11606-4
12	63	Ephemeris type	0
13	65-68	Element number	292
14	69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)	7

Table 2.3: Two-Line Element set format definition, Line 1

Field	Columns	Content	Example
1	01	Line number	1
2	03-07	Satellite number	25544
3	09-16	Inclination [Degrees]	51.6416
4	18-25	Right Ascension of the Ascending Node [Degrees]	247.4627
5	27-33	Eccentricity (decimal point assumed) (Launch number of the year)	0006703
6	35-42	Argument of Perigee [Degrees]	130.5360
7	44-51	Mean Anomaly [Degrees]	325.0288
8	53-63	Mean Motion [Revs per day]	15.72125391
9	64-68	Revolution number at epoch [Revs]	56353
10	69	Checksum (Modulo 10)	00000-0

Table 2.4: Two-Line Element set format definition, Line 2

2.2 Data

The data exchanged between a satellite and the ground stations on Earth can be divided into three different categories: the beacon, the telemetry and the telecommands.

2.2.1 Beacon

A *beacon* is a radio signal transmitted continuously or periodically over a specified radio frequency. It provides a small amount of information such as identification or location, but it can have more applications. Examples of these are: adjust the power of the ground station signal based on the beacon's strength or tune the ground station to compensate the Doppler shift.

2.2.2 Telemetry

Telemetry is the data generated by the payloads and the different sensors of the satellite which is then sent to the ground station. It can be divided into two subcategories.

The *housekeeping data* provides information about the health and operating status of the satellite. Examples of this data can be pressure, voltages and currents, or also bits representing the operational status of all the components as it is shown in Figure 2.5. The size of this data is usually quite small, so a bit rate of only a few hundreds of bits per second is enough to complete the transmission successfully.

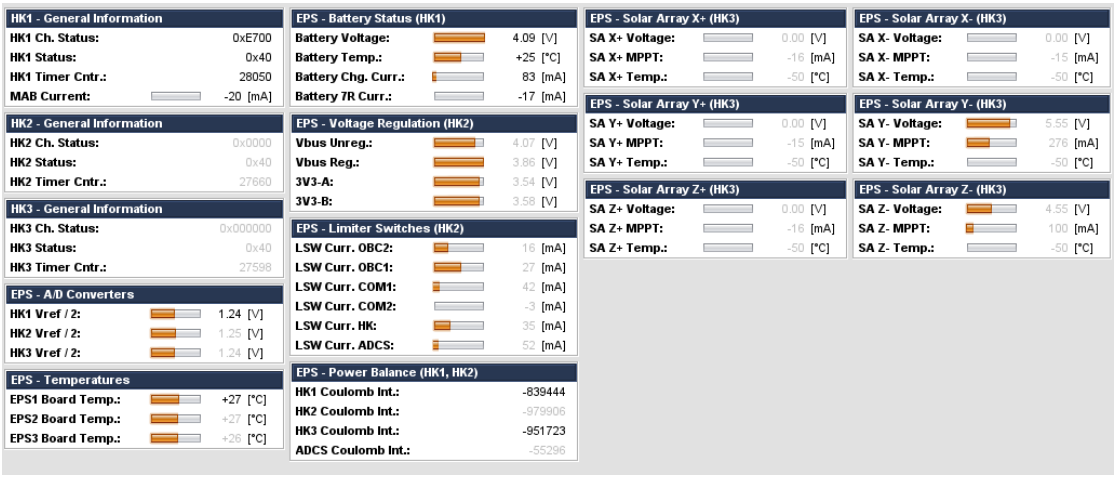


Figure 2.5: Telemetry user interface of the ground station software of the satellite MaSat-1

As its name states the *payload data* is generated by the satellites payloads, which are the reason why the satellite has been developed in the first place. The payload data changes with every mission and needs to be considered individually. For example, scientific or Earth-observing missions normally generate very large data volumes, specially in the form of images, as it can be seen in Figure 2.6, the first picture taken by the Hungarian nanosatellite MaSat-1 [16].

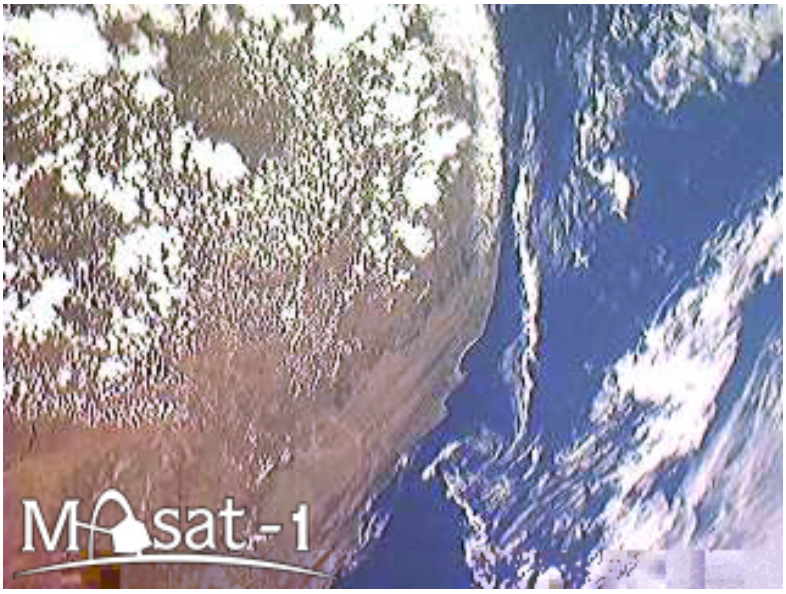


Figure 2.6: Picture of South Africa taken from the nanosatellite MaSat-1

2.2.3 Telecommands

The telecommands are sent from the ground station to the satellite. They are used to remotely control its functions and are divided into three basic types [11]:

- *Low-level on-off commands.* These are logic-level pulses used to set or reset log flip-flops.
- *High-level on-off commands.* Higher-powered pulses, capable of operating a latching relay or RF waveguide switch directly.
- *Proportional commands.* Digital words. Used for purposes such as reprogramming memory locations on the on-board computer or setting up registers in the attitude control subsystem.

2.3 Ground Station

One integral part of every satellite mission is the ground station (Figure 2.7). It works as the first and final piece of the communication link. Its main functions are the following:

- Tracking the satellite to determine its position in orbit.
- Gather data to keep track of the satellite's data and status.
- Command operations to control the different functions of the satellite.
- Process the received engineering and scientific data to present it in the required formats.

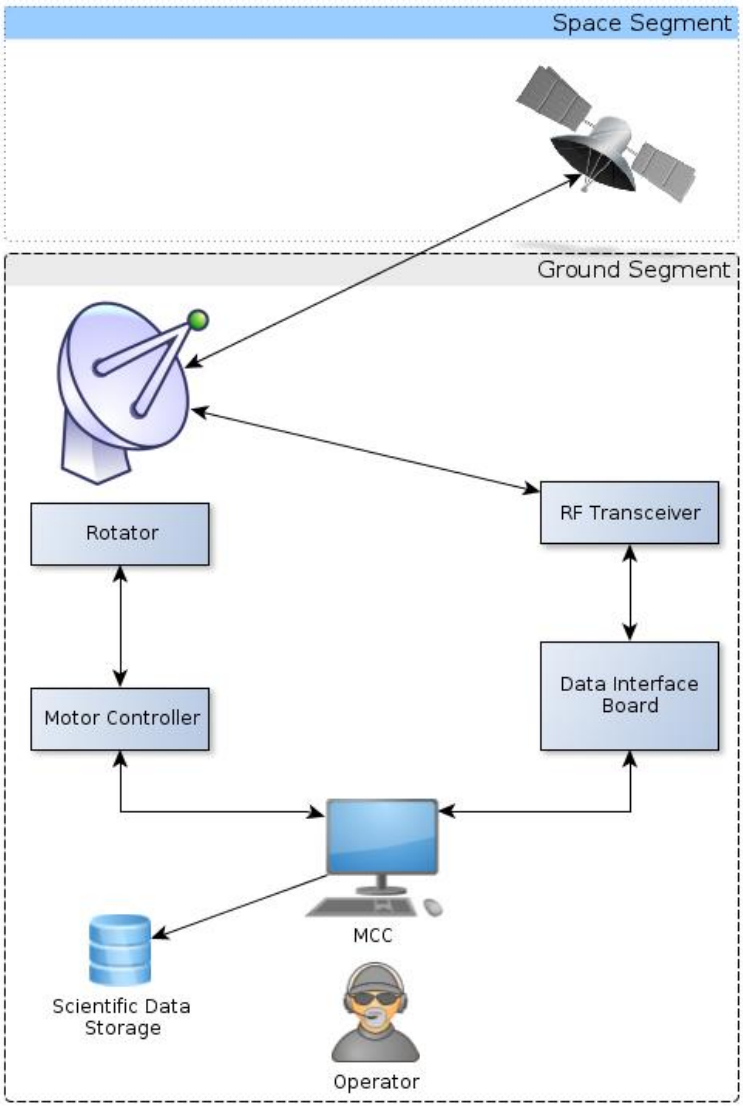


Figure 2.7: Diagram of a ground station

It is important to remember that university satellites are usually classified as amateur satellites. This means that they use amateur radio frequencies and the usage of the ground station is bound to each country's amateur radio regulations.

2.3.1 Ground station hardware

The main components of a ground station are the antenna, the transceiver, the data recorders and the computers and their peripherals.

Antennas

The main hardware component of a ground station is the antenna. Its functions may include tracking, receiving telemetry, sending telecommands, etc.

The frequencies most commonly used for amateur satellites are shown in Table 2.5.

Name	Frequency Range	Wavelength
VHF	30 to 300 Mhz	10 to 1 m
UHF	0.3 to 3 Ghz	1 to 0.1 m
S-Band	2 to 4 Ghz	15 to 7.5 cm
X-Band	8 to 12 Ghz	37.5 to 25 mm

Table 2.5: Common radio frequencies used for amateur satellite communications

Transceiver

A transceiver is a hardware unit containing both a transmitter and a receiver. It acts as an intermediary between the antenna and a computer, changing the radio frequency into bytes and viceversa.

2.3.2 Software

The activity in the ground station does not start when the satellite is passing over it and does not end once the satellite is gone. There are certain tasks that need to be done before, during and after the pass.

Before the satellite arrives it is necessary to determine and predict its orbit. Based on this prediction the software will schedule future passes and generate the command list which will be sent during the pass.

The real-time software comes into operation when the satellite is visible from the ground station. It is in charge of controlling the antenna rotor to follow it across the sky; it will also send telecommands to the satellite and verify their correct reception. In addition, it will receive the data being transmitted from the satellite,

which will be processed later.

Once the satellite is not visible any more the post-pass software comes into play. The data received during the pass is now processed and stored so the specialists can analyse it.

Currently, there are many different kinds of software being used by amateur satellite missions. Examples of this are **GPredict** [17] and **Orbitron** [18], which are used for tracking and prediction, or **Carpcomm** [19], which amongst other functionalities aims to build a network of ground stations.

There is also professional software aiming to build ground station networks. One example is **GENSO**, a project of the European Space Agency (ESA) coordinated by its Education Office. The University of Vigo in Spain hosts the European Operations Node and coordinates the access to the network [20]. At the same time, and as a cooperation with the ESTCube-1 project, CGI Group Inc. is supervising the development of similar solution, **Hummingbird** [21], which will be explained more deeply in the following chapters, as this thesis is part of the mentioned project.

2.3.3 Protocols

A protocol is an agreement between the communicating parties on how communication is to proceed [22]. This section will be focused on the OSI Reference model as well as on some of the most popular protocols for amateur satellite communications.

The OSI Reference Model

The Open Systems Interconnection (OSI) Reference Model was developed in 1983 and revised in 1995. This model deals with connecting systems that are open for communication with other systems. It consists of seven layers which are explained in Table 2.6.

OSI Model			
	Data Unit	**Layer**	**Function**
Host Layers	Data	7. Application	Network process to application.
		6. Presentation	Data representation, encryption and decryption, convert machine dependent data to machine independent data
		5. Session	Interhost communication, managing sessions between applications
	Segments	4. Transport	End-to-end connection, reliability and flow control
Media Layers	Packet/Datagram	3. Network	Path determination and logical adressing
	Frame	2. Data link	Physical addressing
	Bit	1.Physical	Media, signal and binary transmission

Table 2.6: OSI Model [22]

AX.25

AX.25 is a data link layer protocol designed for use by amateur radio operators. It occupies the first, second and third layers of the OSI model. However, AX.25 was developed before the model came into action, so its specification was not written to separate into OSI layers.

The link-layer packet radio transmission takes place in small blocks of data called frames. Those frames are represented in the Figures 2.8 and 2.9.

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	N*8 Bits	16 Bits	01111110

Figure 2.8: AX.25 Supervisory and Unnumbered frames [23]

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	N*8 Bits	16 Bits	01111110

Figure 2.9: AX.25 Information frame [23]

FX.25

FX.25 is an extension to the AX.25 protocol. It has been created to complement the AX.25 protocol, providing an encapsulation mechanism that does not alter the AX.25 data or functionalities. AX.25 packets are easily damaged, and this extension intends to remedy the situation by providing a Forward Error Correction (FEC) capability at the bottom of Layer 2.

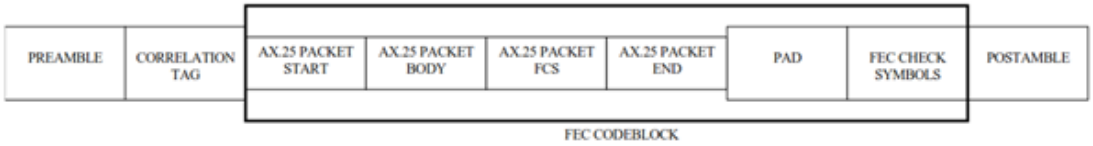


Figure 2.10: FX.25 frame structure [24]

Chapter 3

Hummingbird: the open source platform for monitoring and controlling remote assets

The continuous growth of the popularity of small satellites has been accompanied by an increased interest in creating better solutions for controlling the satellites from Earth. The missions are growing more complex and the use of software oriented for amateurs is starting to prove insufficient. For this reason, nowadays, there are several projects to build professional-like software and ground station networks to control small satellites. This chapter introduces one of them, *Hummingbird* [25] the project into which the work carried out in this thesis will be integrated.

3.1 Overview

Hummingbird is an open source project aiming to create a professional like infrastructure for monitoring and controlling remote assets. It is meant to be highly adaptable, easy scalable and be a baseline so anyone can easily build their own solutions based on this.

It is mainly written in Java [26] and takes advantage to modern software development tools such as Apache Camel [27] and ActiveMQ [28].

3.2 Functionalities

The different modules of the system provide the following functionalities: [29]

- Telemetry limit checking and calibration.
- Telecommands configuration, validation and scheduling.
- Orbit propagation.
- Contact prediction.
- Ground station monitoring.
- Packet coding.
- Data handling.
- Scripting (including most common languages, such as Python and Javascript).
- Storage and distribution using the most common protocols.

3.3 Architecture

Hummingbird is a distributed, component based service-oriented system. It is divided in three tiers: transport, business and presentation.

The transport tier is based on Apache Camel and ActiveMQ. It transports messages between different components and is a black box from the business and presentation tiers point of view.

The business tier contains the business logic of the system. Command creation, limit checking, calibration, scheduling and all other business operations are performed here. This tier does not care about the protocols used to broker the messages, it sends and receives them from a message bus, the transport tier.

The presentation tier is where the data is displayed. There are a number of GUIs available, such as web GUIs, OpenGL based GUIs and OSGI GUIs. Apache Camel is not used for their implementation and they are very independent from the *Hummingbird* infrastructure.

Chapter 4

Requirements

This chapter covers the software requirements for the two modules this thesis is composed of. They are based on the recommendations provided by the scientists working on the ESTCube-1 project. The chapter is organised in three sections, the first one being the requirements which are common to both modules whereas the following two go through each module's requirements more in depth.

4.1 Common information for both modules

4.1.1 General Description

Product Perspective

The modules are part the Hummingbird project based on the advise and needs dictated by the ESTCube-1 team members. For more information about Hummingbird see Chapter 3 and for more information about ESTCube-1 see Chapter 1.

General Constraints

- The modules must be licenced under **Apache License v2.0** [31].
- The use of open source tools is recommended.
- The main programming language must be Java [26].

4.1.2 External Interface Requirements

Software Interfaces

Parameter
The modules will receive Parameters. The *Parameter* type is part of Hummingbird and is represented as follows:

- Numeric value (can be any type).
- Unit of the value.
- Description: additional information about the parameter.
- Timestamp: date and time when the parameter was created.

Apache Camel [27]
Since Hummingbird uses *Apache Camel* for the communication between modules, the parameters for calibration are received and sent back using this system. In addition, Hummingbird has a heartbeat service to check if the module is responding properly. It is necessary to configure the module so it sends and receives messages through Apache Camel.

Communications Interfaces

JMS [30]
The communication interface with the other components in the system is the Java Message Service using Apache Camel. The module is a **JMS client** in a **publish/subscribe model**.

4.1.3 Non-Functional Requirements

Reliability
The software should handle unexpected values correctly. Eg. the value of the parameter is *null* or *NaN*.

Availability
Hummingbird setup can work without the modules. However, they must run for days without problems.

Security
Handled by Hummingbird.

Maintainability
XML configuration at startup.

Portability
Since it is written in Java it should work wherever a JVM is available.

4.2 Calibration module

4.2.1 Introduction

Scope

This software is intended to serve as an independent calibration module for *Hummingbird*. As such, it will receive parameters with raw values, calibrate those values and generate new parameters which will be available for other modules in the system to use. The system must be flexible and allow users to define their own calibration scripts.

Definitions

- **Engineering values**: result of the calibration process.
- **Raw values**: values received from the satellite, before going through the calibration process.
- **Hummingbird:** see Chapter 3.

4.2.2 General Description

Product Perspective

Common to both modules. Please see the section 4.1.1.

Product Functions

- Information input
  - Allow the user to input the calibration information as an XML file.
  - Parse the XML configuration to generate the calibration scripts.
- Calibration process
  - Receive one raw parameter and return one calibrated parameter.
  - Receive one raw parameter and return several calibrated parameters.

  - Receive several raw parameters and return one calibrated parameter.
  - Receive several raw parameters and return several calibrated parameters.

User Characteristics

- Specialists/Scientists
  - Frequency of use: at the moment of inserting the calibration information.
  - Functions used: XML file to insert the calibration information. Other than that, the process is automated.
  - Technical expertise: Comfortable with XML and shell scripting. Also with simple Java programming.

General Constraints

Common to both modules. Please, see section 4.1.1.

User Documentation

- Manual for specialist/scientists who will be writing the calibration scripts. The manual must contain examples of the XML format and the way of representing the calibration scripts.

4.2.3 External Interface Requirements

Software Interfaces

In addition to receiving Parameters this module also generates and sends them. For more information see the section 4.1.2 as the interface is common for both modules.

Communications Interfaces

Common to both modules. Please, see section 4.1.2.

4.2.4 Functional Requirements

Read configuration

Introduction
The first thing the software should do is parsing the configuration files to generate the calibration information.

Inputs
XML files with calibration information for the different subsystems.

Processing

1. Find XML files in the selected location.
2. Find calibration information available in each file.
3. Generate calibration table.

Outputs
The process will generate a table with the calibration information for all the different parameters.

Listen to incoming parameters

Introduction
The module will be waiting for new parameters to arrive. When a parameter is ready for calibration it will be sent to the calibrator.

Inputs
Parameters received through *Apache Camel*.

Processing

1. Receive a parameter.
2. If the parameter is ready for calibration send it to the calibrator.
3. If the parameter needs more parameters to be calibrated wait for those parameters.

Outputs
The output will be one or several parameters which will be sent back to the message queue using *Apache Camel*.

Error Handling

- If no calibrator is found for the parameter log the error and ignore it. No data return to *Apache Camel* is expected.
- If there is a problem with the calibrator log the error and do not return any data through *Apache Camel*.

Calibrate

Introduction
When a parameter is ready for calibration it must be sent to the calibrator, including any extra parameters needed for the calibration and also the calibration information.

Inputs
Parameter to be calibrated plus all extra parameters needed to do so.

Processing

1. Receive parameter(s) needed for calibration.
2. Receive all the calibration information.
3. Use the script to generate the new value.
4. Return the new parameter.

Outputs
The output will be one or several parameters.

Error Handling
If there is an error it must be sent upwards.

4.2.5 Non-Functional Requirements

Common to both modules. Please see section 4.1.3.

4.3 Limit checking module

4.3.1 Introduction

Scope

This software is intended to serve as an independent limit checking module for *Hummingbird*. It will receive a parameter and return information about the state of that parameter in relation to the limits.

Definitions

- **Hummingbird:** see Chapter 3.
- **Parameter**: contains the value.
- **State**: a boolean value reporting the state of the parameter.

4.3.2 General Description

Product Perspective

Common to both modules, please see the section 4.1.1.

Product Functions

- Information input
  - Allow the user to input the limit checking information as an XML file.
  - Parse the XML configuration to generate the limits.

User Characteristics

- Specialists/Scientists
  - Frequency of use: at the moment of inserting the limit checking information.

– Functions used: XML file to insert the limit checking information. Other than that, the process is automated.

– Technical expertise: Comfortable with XML.

General Constraints

In addition to the constraints common to both modules (see section 4.1.1) there must be two options:

- Sanity limits, soft limits and hard limits. (See Figure 4.1).

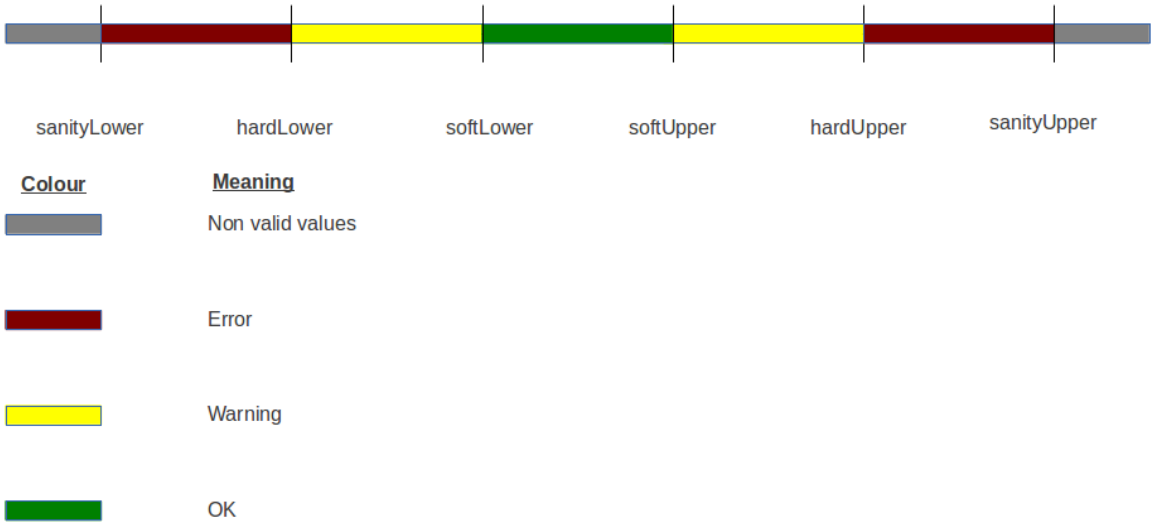


Figure 4.1: Limit checker with sanity limits available

- Soft limits and hard limits only (Figure 4.2).

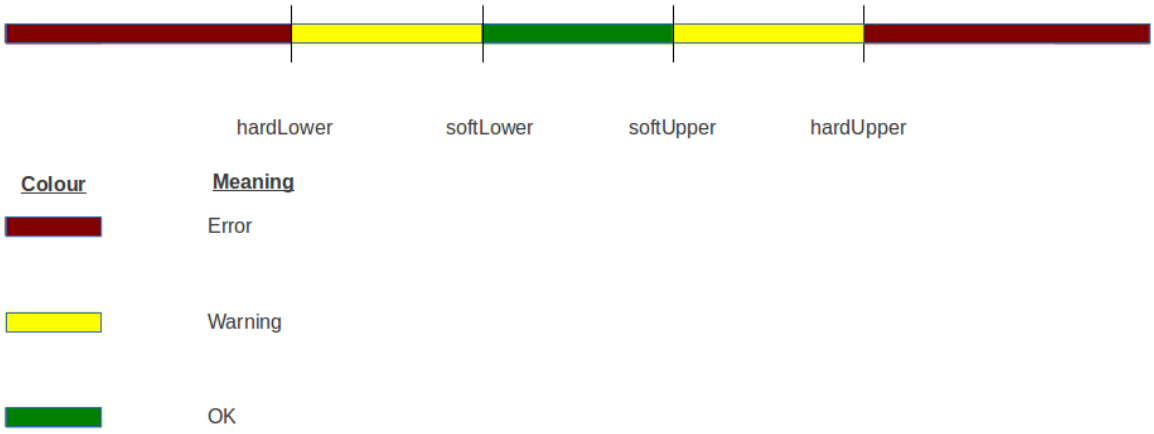


Figure 4.2: Limit checker only with soft and hard limits

User Documentation

- Manual for specialist/scientists who setting up the limits. The manual must contain examples of the XML format.

4.3.3 External Interface Requirements

Software Interfaces

In addition to the common software interfaces for both modules (see section 4.1.2) there is one more software interface to be taken into account.

State

The module will return States. The *State* type is part of Hummingbird and is represented as follows.

- value of the state (boolean).

Communications Interfaces

Common for both modules. Please see the section 4.1.2.

4.3.4 Functional Requirements

Read configuration

Introduction
The first thing the software should do is parse the configuration files to generate the limit checking information.

Inputs
XML files with calibration information for the different subsystems.

Processing

1. Find XML files in the selected location.
2. Find limits information available in each file.
3. Generate limits table.

Outputs
The process will generate a table with the limits information for all the different parameters.

Listen to incoming parameters

Introduction
The module will be waiting for new parameters to arrive. Those parameters will be sent to the limit checker.

Inputs
Parameters received through *Apache Camel*.

Processing

1. Receive a parameter.
2. Send parameter to limit checker.

Outputs
The output will be a list of *State* elements which will be sent back to the message queue using *Apache Camel*.

Error Handling

- If no limit checking information is found for the parameter log the error and ignore it. No data return to *Apache Camel* is expected.
- If there is a problem with the limit checker log the error and do not return any data through *Apache Camel*.

Check limits

Introduction
The software must check the limits, depending on the levels of limits chosen (2 or 3) the comparison will be different.

Inputs
Parameter to be calibrated plus all extra parameters needed to do so.

Processing

1. Receive parameter.
2. Receive the limit checking information.
3. Compare the parameter against the limits.
4. Return the result of the comparison.

Outputs
List of State elements.

Error Handling
If there is an error it must be sent upwards.

4.3.5 Non-Functional Requirements

Common for both modules. Please see section 4.1.3.

Chapter 5

Implementation

This chapter covers the implementation of the two software modules according to the requirements listed in Chapter 4. To begin with, the different technologies used to develop these pieces of software are presented. Afterwards, the design and implementation of both modules is explained, focusing on its structure, the relationships between the different pieces and the algorithms used to achieve the goal.

5.1 Technologies used

As it has been explained previously, the two modules developed as part of the work for this thesis have been designed to be integrated with the Hummingbird project. To do so, Java [26] has been chosen as the main programming language, as it is the language used for the development of Hummingbird. In the same way, Apache Camel [27] and ActiveMQ [28] are used for the communication with the rest of the modules. XStream [32] has been chosen as the library used to parse the XML [33] files used to specify the scientific information.

The final piece of technology used is BeanShell [34], a Java-like scripting language and interpreter which runs in the Java Runtime Environment. The calibration module has been designed to be generic, adaptable to every mission. Also, the goal was to make the calibration information input easy for the scientists, this meaning that there is no need for any difficult Java programming, compilation and so on. BeanShell integrates with the Java code and allows to run those scripts at runtime.

5.2 Implementation of the calibration module

For the sake of clarity, the approach to the explanation will be in small pieces. However, before jumping onto every small piece, it is interesting to look at the package organization of the module.

The software is divided into the following several Java packages:

- **eu.estcube.calibration**: contains the Apache Camel integration. It also contains the main class of the module.
- **eu.estcube.calibration.calibrate**: contains the implementation of the calibrator.
- **eu.estcube.calibration.constants**: contains several constants used throughout the module.
- **eu.estcube.calibration.domain**: contains the data structures used to represent the calibration information and the calibration units.
- **eu.estcube.calibration.processors**: contains the main algorithm for receiving, calibrating and sending the parameters back. Also, the interface implemented by the calibrator can be found here.
- **eu.estcube.calibration.utils**: contains additional utilities. In this case, the tools to manage finding and reading files.
- **eu.estcube.calibration.xmlparser**: contains the tools to parse the information contained in XML format into data which can be used in the module.

5.2.1 Camel Integration

The integration with Camel is a crucial part of the module since it is where it will take the parameters from. There are several classes related to this, the class diagram of this part can be seen in Figure 5.1.

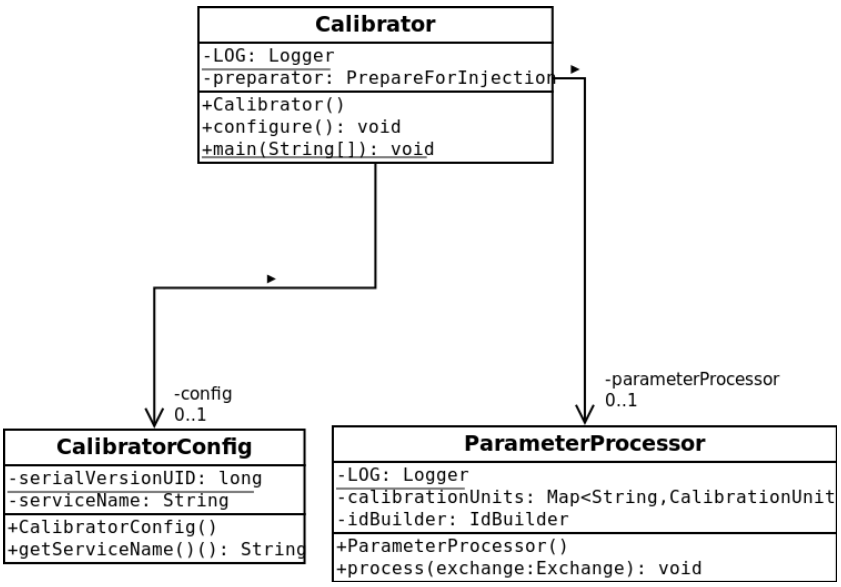


Figure 5.1: Class diagram of the Camel integration

Amongst the three classes represented in Figure 5.1 it is important to highlight two of them: *Calibrator* and *ParameterProcessor*.

Calibrator is the main class of the module. As it is shown in the class diagram there are two methods, the **main** method, where everything starts and the **configure** method. The latter is where the integration with Camel happens, what configures where to get the messages from, how to process them and where to send them afterwards. In addition, *Hummingbird* utilizes a heartbeat system to check if the modules are working correctly, this is also carried on here. Table 5.1 contains a snippet of the code.

```
1
    @Override
3   public void configure() throws Exception {

5       // @formatter:off
        from(StandardEndpoints.MONITORING)
7           .filter(header(StandardArguments.CLASS)
            .isEqualTo(Parameter.class.getSimpleName()))
9           .process(parameterProcessor)
            .split(body())
11          .process(preparator)
            .to(StandardEndpoints.MONITORING);
13
        BusinessCard card = new ↙
            ↳ BusinessCard(config.getServiceId(), ↙
            ↳ config.getServiceName());
15      card.setPeriod(config.getHeartBeatInterval());
        card.setDescription(String.format("Calibrator; version: ↙
            ↳ %s", config.getServiceVersion()));
17      from("timer://heartbeat?fixedRate=true&period=" + ↙
            ↳ config.getHeartBeatInterval())
            .bean(card, "touch")
19          .process(preparator)
            .to(StandardEndpoints.MONITORING);
21      // @formatter:on

23  }
```

Table 5.1: Camel integration Java code for the calibrator

Focusing on the part where the module receives and sends the parameters we can see that:

- Where it gets the messages from –> *from(StandardEndpoints.MONITORING)*
- It only gets messages containing parameters –> *.filter(header(StandardArguments.CLASS) .isEqualTo(Parameter.class.getSimpleName()))*
- What to do with the received message –> *.process(parameterProcessor)*
- Since the result of the processed message is a list and it is necessary to send the parameters one by one, that result must be split. –> *.split(body())*
- Send it back to the messaging service –> *.process(preparator) .to(StandardEndpoints.MONITORING);*

The second part - from line 14 and below - contains the heartbeat system.

ParameterProcessor contains the following:

- Part of the Camel integration.
- Code to load the calibration information from the configuration files.
- Algorithm to process the received parameters.

The code corresponding to the Camel integration is shown in table 5.2. The other two parts will be explained in the following subsections.

```
2     /** @{inheritDoc . */
      @Override
4     public void process(Exchange exchange) throws Exception {

6         Message in = exchange.getIn();
          Message out = exchange.getOut();
8         out.copyFrom(in);

10            //The main algorithm would be placed here

12        out.setBody(calibratedParameters);

14    }
```

Table 5.2: Java code showing the Camel integration of *ParameterProcessor*

5.2.2 Loading the calibration information

The first action point when the module is initiated is loading the calibration information. This will read the information from the configuration files written by the specialists and will create a series of calibration units which will later be used to calibrate the incoming parameters.

Figure 5.2 shows the different classes involved in this process. They can be organised as follows:

- Main class: *ParameterProcessor*
- Data structures:
  - *CalibrationUnit*
  - *InfoContainer*
- Utils:
  - *InitCalibrationUnits*
  - *InitCalibrators*
  - *FileManager*
- Parser:
  - *Parser*
  - *HashMapConverter*

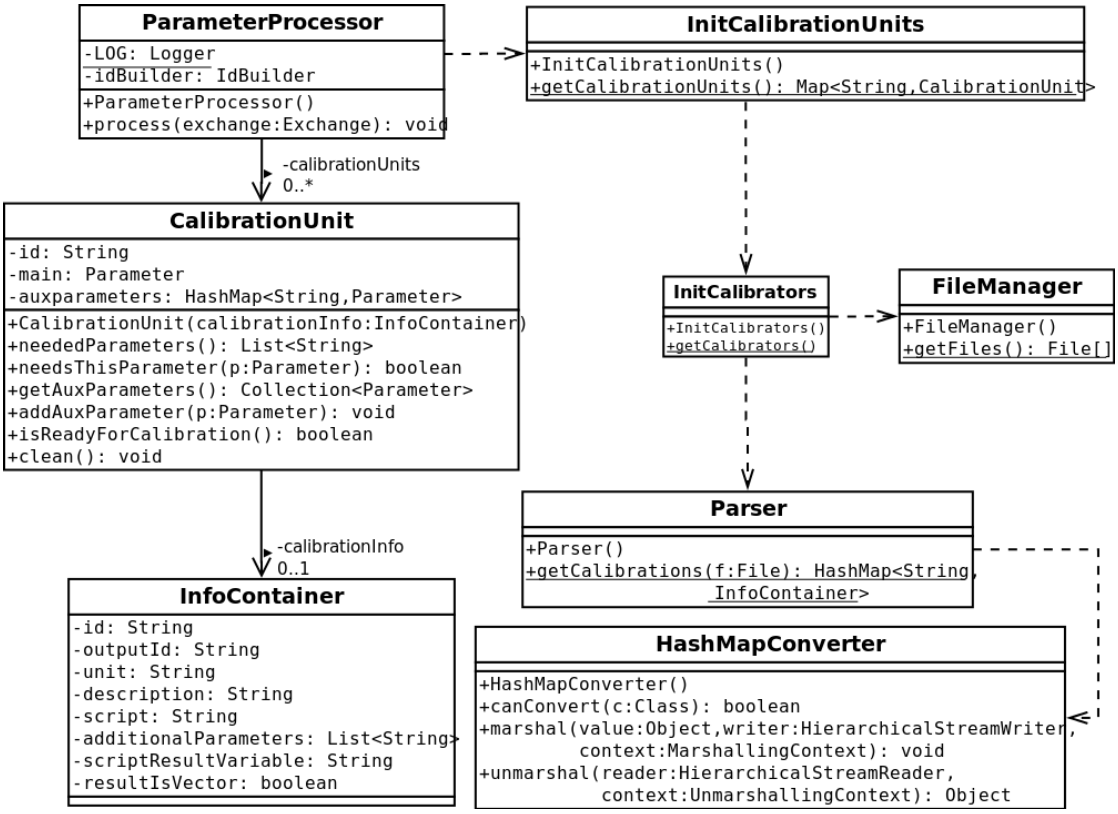


Figure 5.2: Diagram of the classes involved in loading the calibration information onto the system

The best way to see how these classes interact with each other is by looking at its sequence diagram (Figure 5.3). The main class is *ParameterProcessor*, where the calibration information will be stored in the form of a *HashMap* of calibration units. The reason for choosing this data structure is its efficiency, as it provides constant-time performance for the input and retrieval of information [35]. The process begins by *ParameterProcessor* asking *InitCalibrationUnits* to initialize them. To do so, the calibration units need the calibration information (calibrators), which is initialized by *InitCalibrators*. *InitCalibrators* is the class which manages the access to the information in the files; first it finds the corresponding XML files to later parse each of them, creating the calibrators. With this calibrators, *InitCalibrationUnits* creates them, and then returns them to the main class where they are ready to receive the incoming parameters.

There is one class present in the class diagram in Figure 5.2 which is not present in Figure 5.3, *HashMapConverter*. This is because this class is managed by *XStream*, the external library used to simplify the XML accessing and parsing.

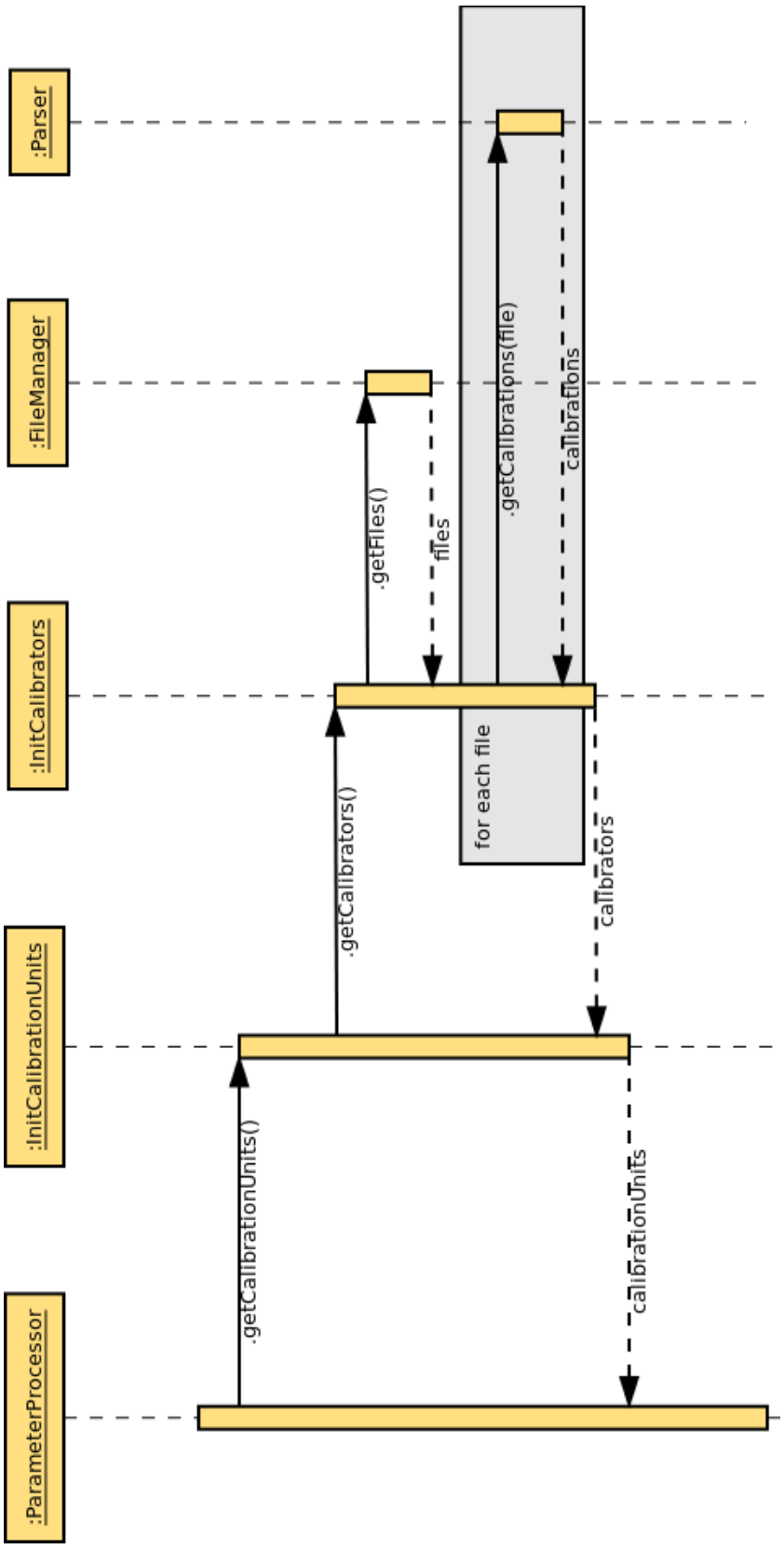


Figure 5.3: Sequence diagram which represents the interactions between the different classes present when loading the calibration information

The data structure created to represent the calibration information is *InfoContainer* and it is formed by these components:

- **id**
  - Type: String
  - Content: name of the parameter to be calibrated
- **outputId**
  - Type: String
  - Content: name of the engineering parameter
- **unit**
  - Type: String
  - Content: unit in which the calibrated value is represented
- **Description**
  - Type: String
  - Content: description of the parameter
- **additionalParameters**
  - Type: List of Strings
  - Content: List with the names of any extra parameters needed for the calibration
- **resultIsVector**
  - Type: boolean
  - Content: *true* if the result of the calibration is a vector, $false$ if the result of the calibration is an individual value
- **scriptResultVariable**
  - Type: String
  - Content: name of the variable which will contain the result in the script
- **script**
  - Type: String
  - Content: calibration script

This data structure is later stored within another data structure, *CalibrationUnit*. The reason for using this second data structure is the way parameters are received from Apache Camel, one by one. If all the calibrations were just simple one-parameter calibrations that would not be necessary. However, some parameters might need information from others to be calibrated. Thus, they need to be

sent as a whole unit to the method which will generate the engineering values. *CalibrationUnit* is formed by the following components:

- Attributes:
  - **id**
    - Type: String
    - Content: name of the parameter to be calibrated
  - **main**
    - Type: Parameter
    - Content: parameter which will be calibrated
  - **auxParameters**
    - Type: HashMap of Parameters
    - Content: extra parameters needed to calibrate the main one
- Amongst others, *CalibrationUnit* can perform the following actions:
  - **neededParameters()**: returns the parameters listed as necessary for the calibration.
  - **needsThisParameter()**: checks whether or not a particular parameter is needed for the current calibration unit.
  - **addAuxParameter()**: adds an extra parameter when needed.
  - **isReadyForCalibration()**: checks that all the needed parameters are in place. Only when this check returns *true* the calibration unit is sent to the calibrator.
  - **clean()**: once the calibration unit has been sent to the calibrator, it is cleaned so it can be used for the next time that parameters are received. This means emptying the main and auxiliary parameters.

5.2.3 Calibration

The calibration process can be divided in two parts. The first one is managing the parameters that arrive from other modules, prepare the calibration units and send back the results. The second one is the actual calibration.

Figure 5.4 represents the class diagram of this part of the software. There are three classes which have been seen in previous sections —*ParameterProcessor*, *CalibrationUnit* and *InfoContainer*— and two new ones which are:

- *ParameterCalibrator*: Interface representing the method that the calibrator must contain.

- *Calibrate*: Implementation of the previous interface, where the actual calibration is performed. This class is generic class. Its generic type T extends from Java Number, which means any of the Java Number subtypes can be used when instantiating it. It currently is in the form of a Double, but it can be easily modified if ever needed.

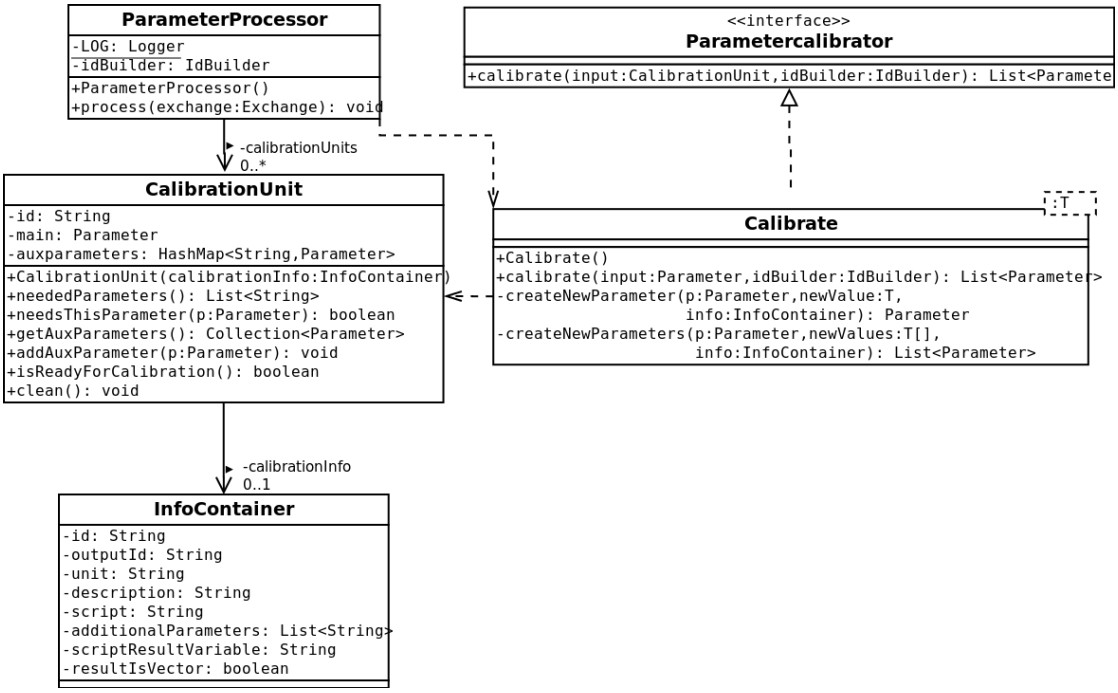


Figure 5.4: Diagram representing the classes involved in the calibration process

Figure 5.5 is a flow chart representing the algorithm used to manage the received parameters, in combination with the sequence diagram of Figure 5.6 they show what the steps in the algorithm are and which parts of the software performs then. As it was previously stated, the main class is *ParameterProcessor*, where the calibration units have already been created. When a parameter is received, if its corresponding calibration unit is available it is included as its main part (if it is not present, the process ends and the error is logged). Afterwards, the algorithm goes through every calibration unit doing the following:

1. Check if the parameter is needed for the calibration unit.
2. If the step 1 is true, add the parameter as an auxiliary parameter for the calibration.
3. Check if the calibration unit is ready for calibration.
4. If the 3 is true, calibrate and save the results in a list. Finally, clean the calibration unit.

After the whole process is completed the results are sent back to Apache Camel to make them available for the rest of the system.

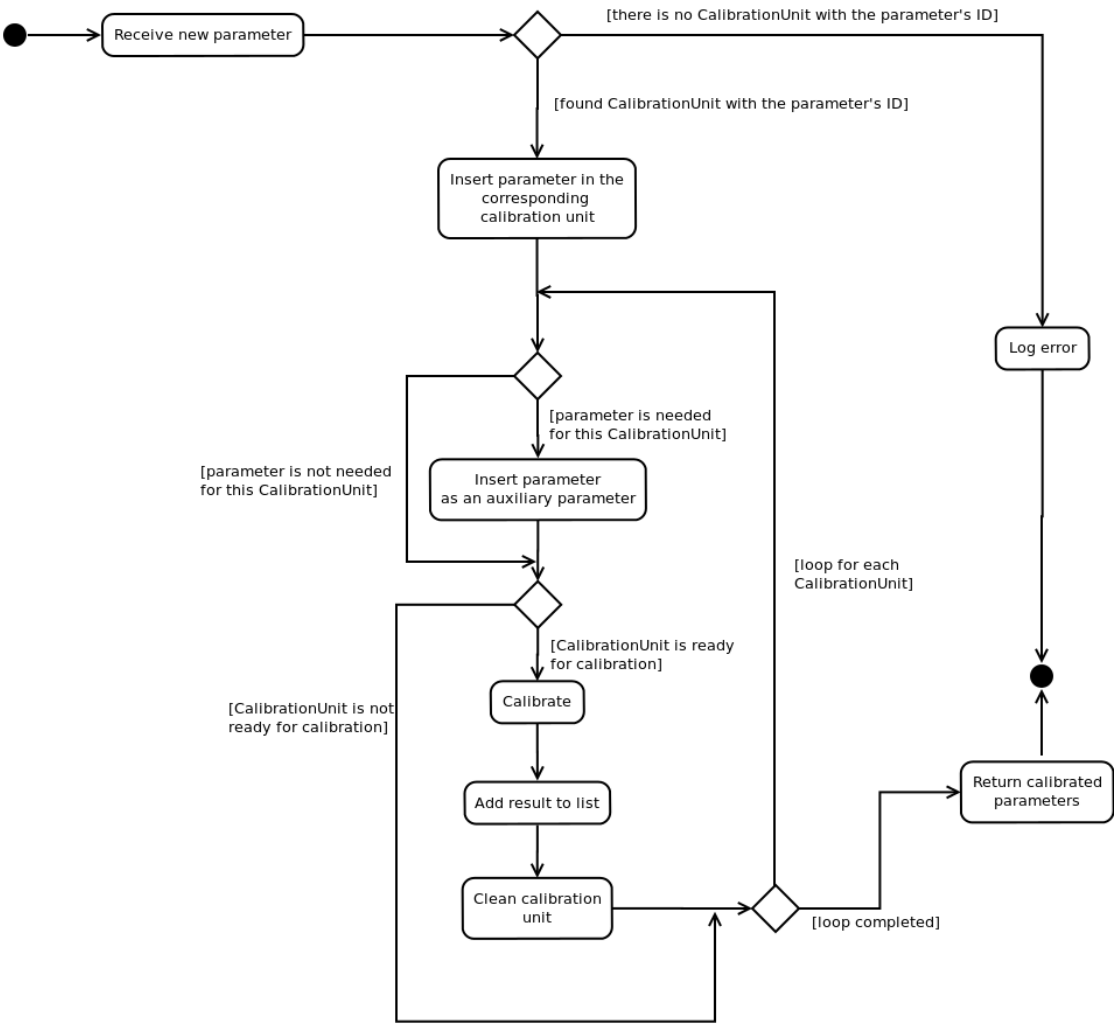


Figure 5.5: Flow chart of the algorithm to manage incoming parameters in the calibration module

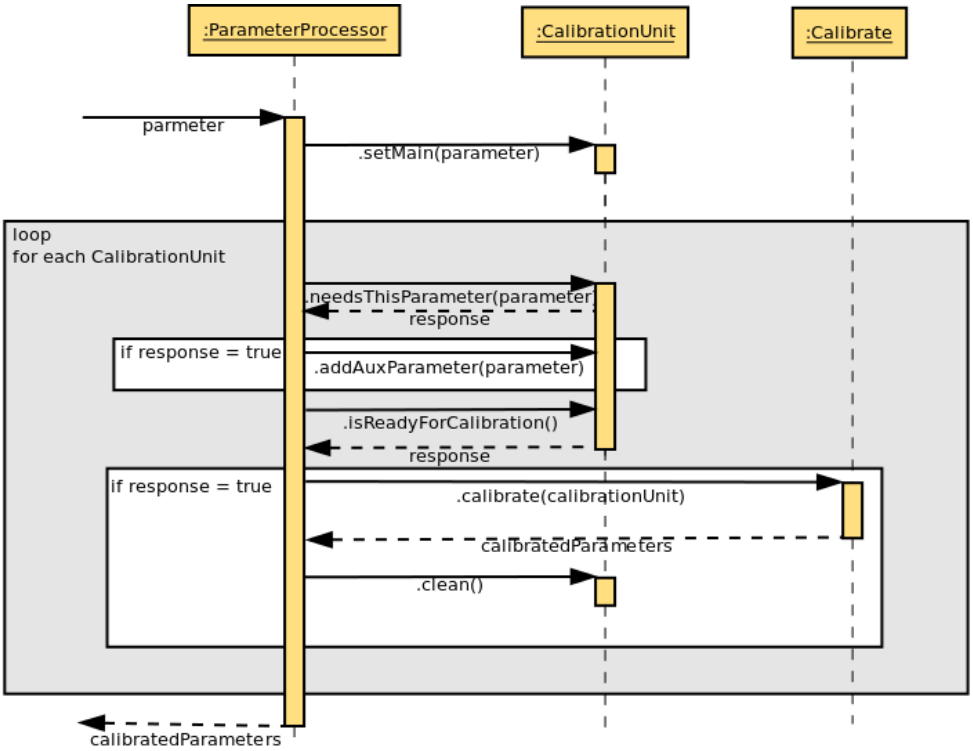


Figure 5.6: Sequence diagram describing the interactions between the different classes when managing incoming parameters in the calibration module

The part of evaluating the raw parameters using the calibration script is left in the hands of BeanShell. The way to evaluate a script with this library is very simple as it can be seen in Table 5.3.

```
Interpreter interpreter = new Interpreter();
interpreter.eval(calibrationScript);
```

Table 5.3: Java code used to evaluate a script with *BeanShell*

Table 5.4 shows the way information is retrieved from the interpreter and how the parameters with the engineering values are created. The actions to be taken change depending on the result being a vector or not.

```
if (input.getCalibrationInfo().isResultIsVector()) {

        T[] calibratedValues = (T[]) ↙
            ↳ interpreter.get(input.getCalibrationInfo()
            .getScriptResultVariable());
        output.addAll(createNewParameters(input.getMain(), ↙
            ↳ calibratedValues, input.getCalibrationInfo()));

    } else {

        T calibratedValue = (T) ↙
            ↳ interpreter.get(input.getCalibrationInfo()
          .getScriptResultVariable());
        output.add(createNewParameter(input.getMain(), ↙
            ↳ calibratedValue,
                input.getCalibrationInfo()););

    }
```

Table 5.4: Java code used to retrieve the information from the interpreter and generate the new parameters

5.3 Implementation of the limit checking module

This module also has a very similar structure to the calibration one. The explanation will once again be divided in small pieces, some of them very similar to the ones already explained for the calibration module. The overall package structure of the module is the following:

- **eu.estcube.limitchecking**: contains the Apache Camel integration and the main class of the module.
- **eu.estcube.limitchecking.checklimits**: contains the classes where the limit checking is performed.
- **eu.estcube.limitchecking.constants**: contains several constants which are used throughout the module.
- **eu.estcube.limitchecking.domain**: contains the data structure used to represent the limits information.
- **eu.estcube.limitchecking.processors**: contains the main algorithm for receiving, checking the limits and sending the results back. In addition, the interface implemented by the limit checker can be found here.

- **eu.estcube.limitchecking.utils**: contains additional utilities. In this case, the tools to manage finding and reading files.
- **eu.estcube.limitchecking.xmlparser**: contains the tools to parse the information contained in XML format into data which can be used in the module.

5.3.1 Camel integration

The integration with Apache Camel is done in the exact same way as in the calibration module. Figure 5.7 contains a diagram of the classes involved in this process. The classes change their name (*Calibrator* to *LimitChecking* and *CalibratorConfig* to *LimitCheckingConfig*) and the **split** option is removed (compare to Tables 5.1 and 5.5), as there is no need to split results received from *ParameterProcessor*. There are also some minor changes in the latter, but those are related to the limit checking and not to the Camel integration. For more information please see section 5.2.1.

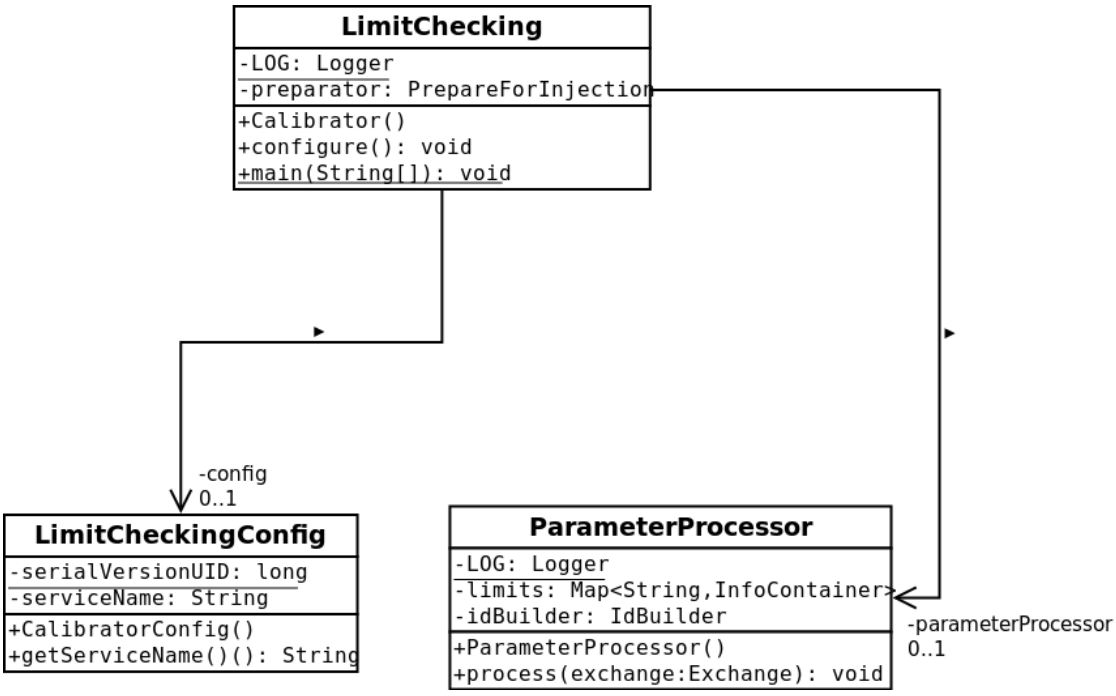


Figure 5.7: Class diagram of the Camel integration

```
2       @Override
        public void configure() throws Exception {
4
            // @formatter:off
6           from(StandardEndpoints.MONITORING)
                .filter(header(StandardArguments.CLASS)
8               .isEqualTo(Parameter.class.getSimpleName()))
                .process(parameterProcessor)
10              .process(preparator)
                .to(StandardEndpoints.MONITORING);
12
            BusinessCard card = new ↙
                ↳ BusinessCard(config.getServiceId(), ↙
                ↳ config.getServiceName());
14          card.setPeriod(config.getHeartBeatInterval());
            card.setDescription(String.format("Calibrator; version: ↙
                ↳ %s", config.getServiceVersion()));
16          from("timer://heartbeat?fixedRate=true&period=" + ↙
                ↳ config.getHeartBeatInterval())
                .bean(card, "touch")
18              .process(preparator)
                .to(StandardEndpoints.MONITORING);
20          // @formatter:on

22      }
```

Table 5.5: Camel integration Java code for the limit checker

5.3.2 Loading the limits information

This is also done in the same way as it is performed in the calibration module. The first action when the module is initiated is loading the limits information. This means reading the information from the configuration files and creating the limits which will be later used to compare against the incoming parameters. Figure 5.8 shows the different classes involved in this process. They can be organised as follows:

- Main class: *ParameterProcessor*
- Data structure: *InfoContainer*
- Utils:
  - *InitLimits*
  - *FileManager*
- Parser:
  - *Parser*
  - *HashMapConverter*

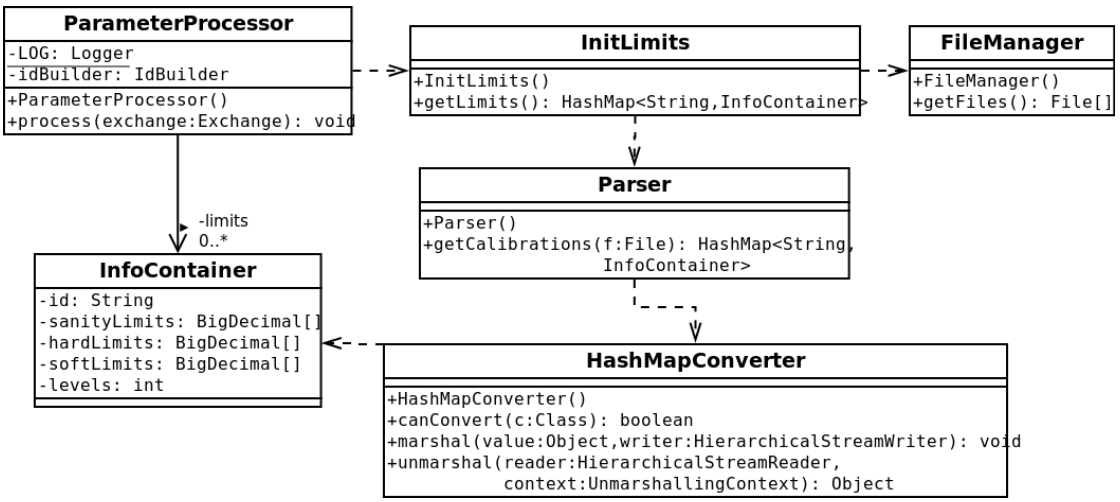


Figure 5.8: Diagram of the classes involved in loading the limits information onto the system

Figure 5.9 shows the sequence of message exchanges between the different classes involved in this process. Just as in the calibration module, the process begins at *ParameterProcessor* and the limits will also be stored in a *HashMap*, each entry corresponding to a different parameter. *InitLimits* is the class in charge of populating that HashMap and to do so it follows the exact same process as the one explained for the calibration module.

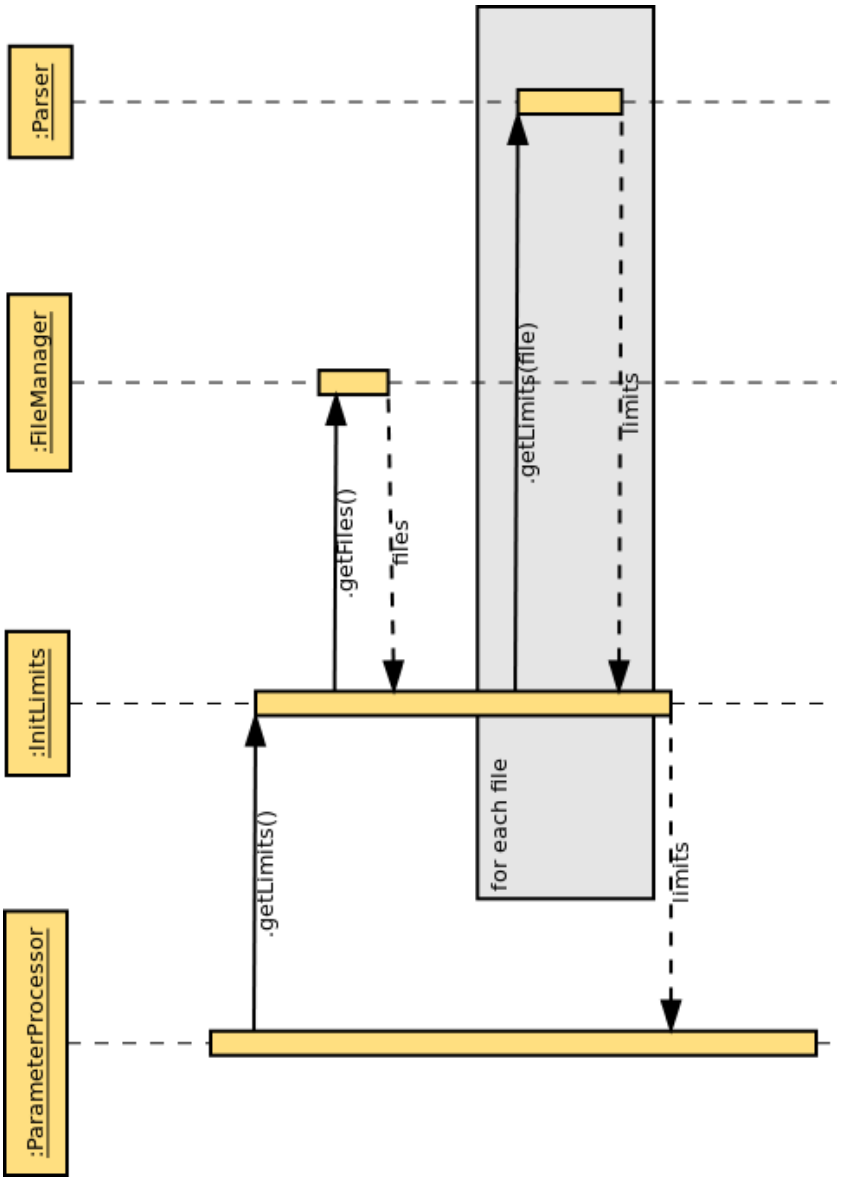


Figure 5.9: Sequence diagram which represents the interactions between the different classes present when loading the limits information

The data structure used to represent the limits information is, as it was in the previous module, *InfoContainer*. However, its inner structure differs to the one which was previously used:

- **id**
  - Type: String
  - Content: name of the corresponding parameter.
- **sanityLimits**
  - Type: Array of *BigDecimal* [36]. This number format has been chosen as it provides high precision, avoiding rounding errors from other types, such as *double*.
  - Content: lower limit in the first position and and upper limit in the second. This limits are optional, if enabled, four regions are available (discard, error, warning and OK). Any values below the lower or above the upper limits are discarded.
- **hardLimits**
  - Type: Array of *BigDecimal*.
  - Content: lower limit in the first position and upper limit in the second. Anything between this limits and the soft limits is in the warning zone. Anything below the lower or above the upper limits is erroneous.
- **softLimits**
  - Type: Array of *BigDecimal*.
  - Content: lower limit in the first position and upper limit in the second. Anything within these limits is in the OK region.
- **levels**
  - Type: Integer
  - Content: automatically generated. Its value is 4 if sanity limits are available,f or 3 if they are not.

5.3.3 Limit checking

The process to check the limits of a parameter can also be divided in two, in the same way as the calibration module.

The different classes involved in this part are represented in the class diagram in Figure 5.10. There are three new classes used:

- *CheckLimits*: abstract class which implements the common methods used independently of the sanity limits being enabled or not. **isInErrorRegion()** and **checkLimits()** change depending on that fact, so they are implemented by its subclasses.
- *CheckLimitsThreeLevels*: subclass of *CheckLimits*. Used when the sanity limits are disabled.
- *CheckLimitsFourLevels*: subclass of *CheckLimits*. Used when the sanity limits are enabled.

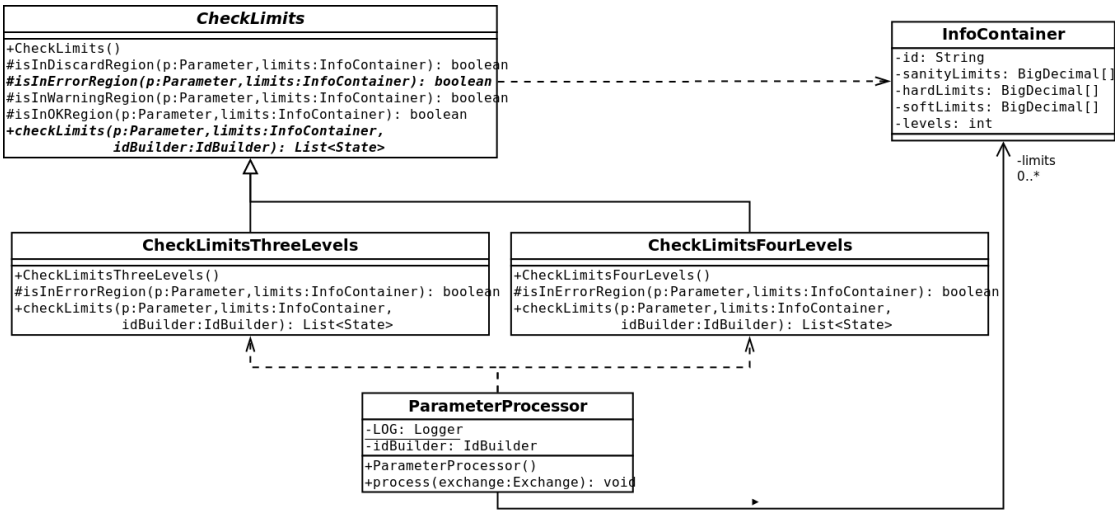


Figure 5.10: Diagram representing the classes involved in the limit checking process

The flow of the process can be seen in Figure 5.11 whereas Figure 5.12 shows the sequence diagram with the messages between the classes. For the sake of clarity, *CheckLimits* should be interpreted as *CheckLimitsThreeLevels* or *CheckLimitsFourLevels*, depending on the case. This algorithm is much simpler than the one used for the calibration; the main class is *ParameterProcessor*, where the limits information is stored. When a parameter is received, the first step in the algorithm is checking for its limits. If they are not present the process will end and error will be logged. If everything goes correctly, the parameter will be sent to either *CheckLimitsThreeLevels* or *CheckLimitsFourLevels*.

Per request from the *Hummingbird* architect, the result is returned as a list of *State*. The list has four elements, being:

- Discard region (if the sanity limits are disabled this state is automatically set to false)
- Error region
- Warning region
- OK region

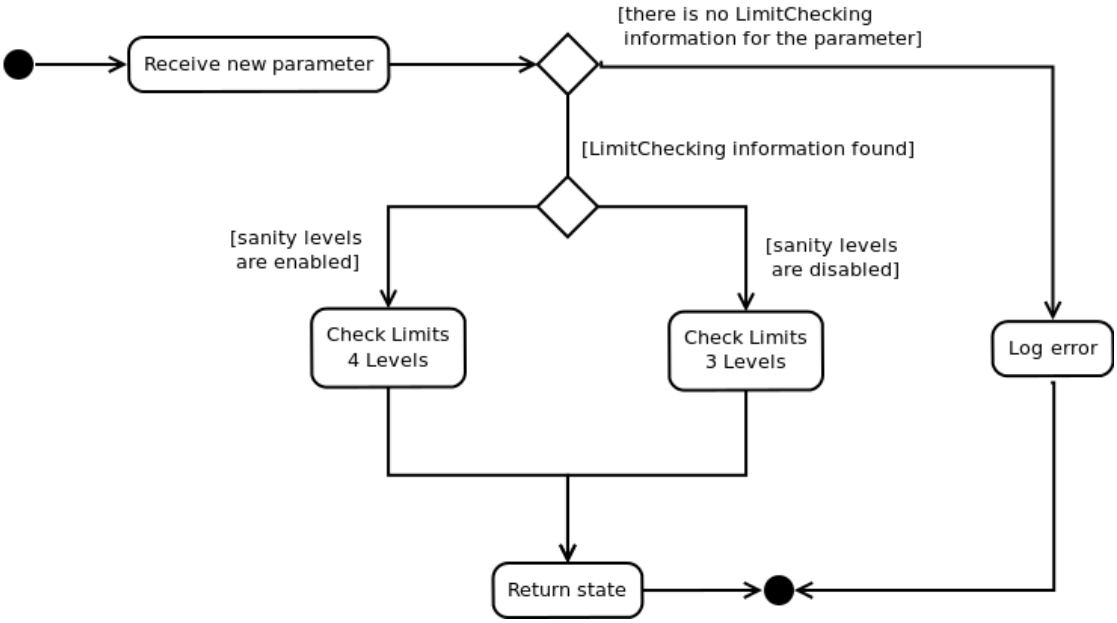


Figure 5.11: Diagram representing the classes involved in the limit checking process

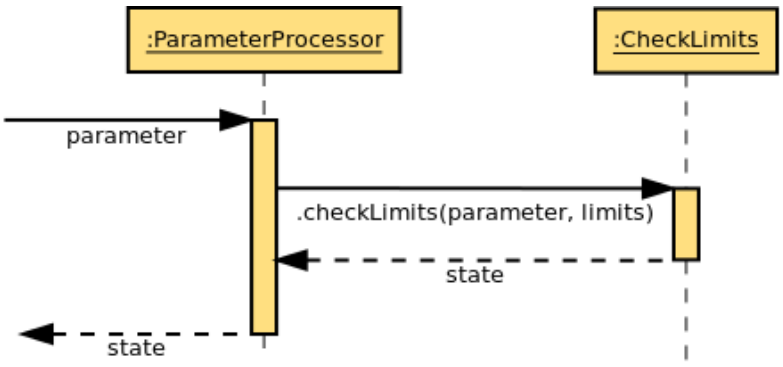


Figure 5.12: Diagram representing the classes involved in the limit checking process

Chapter 6

User manual

6.1 Calibration module

This short user manual covers the use of the calibration module. The process is fully automated, so the user only needs to configure the pertinent XML file containing the information related to all the parameters which need to be calibrated.

There should be one file per subsystem. This way, the person who is making the changes will not have to be worried about modifying some other parts they do not understand. It is advisable that each file is called as the corresponding subsystem.

The location of the folder where the XML files are stored is fully configurable by a system property. It can be set like this: **-Dpath="/path/to/the/folder"**.

6.1.1 Structure of the XML file

The XML file follows the format of Table 6.1

```
1
<calibration>
3    <entry>
        <id></id>
5       <description></description>
        <outputId></outputId>
7       <unit></unit>
        <scriptInfo>
9           <isVector></isVector>
            <resultVariable></resultVariable>
11          <auxParameters></auxParameters>
            <script></script>
13      </scriptInfo>
    </entry>
15 </calibration>
```

Table 6.1: Structure of the XML file used to configure the calibrators

- **id**: name of the parameter to calibrate.
- **Description**: description of the parameter.
- **outputId**: name of the parameter generated after the calibration. If left blank, it will be the same as **id**.
- **unit**: Units in which the value is represented.
- **isVector**: *true* if the result of the calibration is a vector with several values (which generates several new parameters) or $false$ if the calibration returns a single value.
- **resultVariable**: variable in the script in which the result will be stored.
- **auxParameters**: if the are any extra parameters needed for the calibration process it is necessary to list them here separated by commas. Please note that if the extra parameters also need to be calibrated the parameters needed for their calibration must also be included here in addition to the original ones.
- **script**: script to generate the calibrated value. Note that if extra parameters are needed, their calibration scripts must be included here, not the parameter name.

6.1.2 Example of simple calibration

```
1
<calibration>
3     <entry>
          <id>parameterA</id>
5         <description>Example of parameter for
           simple calibration</description>
7         <outputId>generatedA</outputId>
          <unit>E</unit>
9         <scriptInfo>
              <isVector>false</isVector>
11            <resultVariable>result</resultVariable>
              <auxParameters></auxParameters>
13            <script>result = (parameterA*779.098)/35.28</script>
          </scriptInfo>
15    </entry>
</calibration>
```

Table 6.2: Example of simple calibration

Table 5.7 represents the simplest example of calibration information. **parameterA** is the parameter to be calibrated and the user has chosen that the name of the calibrated parameter will be **generatedA**. The information about the calibration script states that the result will not be a vector and the value after the calculations will be stored in a variable called **result**. There are no extra parameters needed for the process to be carried on.

6.1.3 Example of calibration dependent on other parameters

```
<calibration>
    <entry>
        <id>parameterA</id>
        <description>Example of parameter which depends
         on others to be calibrated</description>
        <outputId></outputId>
        <unit>E</unit>
        <scriptInfo>
            <isVector>false</isVector>
            <resultVariable>result</resultVariable>
            <auxParameters>parameterB,parameterC</auxParameters>
            <script>result = (parameterA*(parameterB*2345/37))
            /3145.2839 + (parameterC*2)</script>
        </scriptInfo>
    </entry>
</calibration>
```

Table 6.3: Example of calibration dependent on other parameters

Table 5.8 shows an example of a parameter which depends on others for calibration. Again, **parameterA** is the name of the parameter to be calibrated. In this case the user has not selected an output ID, so it will by default be the same as the input. The result of the calibration will not be a vector and it needs **parameterB** and **parameterC** to be calibrated. The calibration script can be explained as follows:

- Calibration script for **parameterA**: $result$ = (($parameterA$*($parameterB$)) /3145.2839) + ($parameterC$)
- The user must specify **parameterB**'s calibration script: $parameterB * 2345/37$
- Same thing with **parameterC**: $parameterC * 2$
- The final result is what can be seen in the example: $result$ = ($parameterA * (parameterB * 2345/37))/3145.2839 + (parameterC * 2)$

6.1.4 Example of calibration dependent on other parameters which are dependent on others

```
1
<calibration>
3     <entry>
          <id>parameterA</id>
5         <description>Example of parameter which depends
           on others to be calibrated. Those other depend on ↙
              ↳ others.</description>
7         <outputId></outputId>
          <unit>E</unit>
9         <scriptInfo>
              <isVector>false</isVector>
11            <resultVariable>result</resultVariable>
              <auxParameters>parameterB,parameterC,parameterD</auxParameters>
13            <script>result = (parameterA*2)/((parameterB*4) + ↙
                  ↳ 5*parameterC - parameterD/4))</script>
          </scriptInfo>
15    </entry>
</calibration>
```

Table 6.4: Example of calibration dependent on other parameters which also depend on others

Table 6.4, which illustrates this example can be explained as:

- Parameter to be calibrated: **parameterA**
- Auxiliary parameters:
  - parameterA's dependency: **parameterB**
  - parameterB's dependency: **parameterC** and **parameterD**
  - Calibration script for parameterC: $5 * parameterC$
  - Calibration script for parameterD: $parameterD/4$
  - Calibration script for parameterB: $((parameterB*4)+5*parameterC-parameterD/4))$
  - Calibration script for parameterA: $(parameterA * 2)/((parameterB * 4) + 5 * parameterC - parameterD/4))$

6.1.5 Example of the result of the calibration being a vector

```
<calibration>
    <entry>
        <id>parameterA</id>
        <description>Example of parameter whose calibration returns a vector</description>
        <outputId></outputId>
        <unit>E</unit>
        <scriptInfo>
            <isVector>true</isVector>
            <resultVariable>result</resultVariable>
            <auxParameters></auxParameters>
            <script>int[] result = {parameterA*2, parameterA*3, parameterA*4};</script>
        </scriptInfo>
    </entry>
</calibration>
```

Table 6.5: Example of calibration which returns a vector as result

The module supports the interpretation of Java code and shell scripts. This example shows a short piece of Java code which will return a vector of Integer elements. Also, it is needed to state that the result will be a vector.

6.2 Limit checking module

This subsection covers the user manual for the limit checking module. The process is fully automated, so the user only needs to configure the pertinent XML file containing the information related to the limits of every parameter.

There can be as many files as needed, although it is recommended to have one file per subsystem. This way, the user will not have to be worried about modifying some other parts they do not understand. It is advisable that each file is called as the corresponding subsystem.

The location of the folder where the XML files are stored is fully configurable by a system property. It can be set like this: **-Dpath="/path/to/the/folder"**.

The format of the XML file is represented in Table 6.6.

```
1
<limitChecking>
3    <entry>
        <id></id>
5       <limits>
            <sanityLower></sanityLower>
7           <hardLower></hardLower>
            <softLower></softLower>
9           <softUpper></softUpper>
            <hardUpper></hardUpper>
11          <sanityUpper></sanityUpper>
        </limits>
13   </entry>
</limitChecking>
```

Table 6.6: Structure of the XML file used to configure the limits

- **id**: name of the parameter to calibrate which limits are to be checked.
- **Sanity limits** (optional): if the value is below the lower limit or above the upper limit it is discarded.
- **Hard limits**:
  - If the sanity limits are available anything between these limits and the sanity limits is considered an error.
  - If the sanity limits are disabled anything below the lower limit or above the upper limit is considered an error.
- **Soft limits**:
  - Anything between the lower and upper soft limits is considered an OK value.
  - Anything between the soft limits and the hard limits is considered OK, but with a warning.

6.2.1 Example of configuration with sanity limits

```
<limitChecking>
    <entry>
        <id>parameterA</id>
        <limits>
            <sanityLower>-100</sanityLower>
            <hardLower>-75</hardLower>
            <softLower>-20</softLower>
            <softUpper>20</softUpper>
            <hardUpper>75</hardUpper>
            <sanityUpper>100</sanityUpper>
        </limits>
    </entry>
</limitChecking>
```

Table 6.7: Limit checking with sanity limits

6.2.2 Example of configuration without sanity limits

```
<limitChecking>
    <entry>
        <id>parameterA</id>
        <limits>
            <hardLower>-75</hardLower>
            <softLower>-20</softLower>
            <softUpper>20</softUpper>
            <hardUpper>75</hardUpper>
        </limits>
    </entry>
</limitChecking>
```

Table 6.8: Limit checking without sanity limits

Chapter 7

Conclussions

This thesis has presented the development of a ground control software for Aalto-1 and ESTCube, satellites belonging to the increasingly popular nanosatellite family. The ground control software chosen by these two satellite missions is *Hummingbird*, an open source project aiming to create software which can be easily adaptable for any kind of mission as well as creating a network of ground stations. It is being developed by CGI Group Inc. in cooperation with the University of Tartu and some external collaborators, such as the author of this thesis.

As part of this collaboration, two *Hummingbird* modules have been designed and implemented. The first one being the telemetry calibration module and the second one the limit checker.

The most challenging parts of this work have been related to the calibration module. First, an algorithm adapted to the way modules communicate in *Hummingbird* had to be designed. The other challenge was finding a way to allow scientists to input calibration information without the need of changing the Java code; the solution chosen was to use an embedded interpreter, so anyone with knowledge of scripting would be able to create their own calibration scripts.

The result has been two fully configurable and adaptable modules, which allow to calibrate and check the limits of the parameters received from the satellite. If there are changes in the mission, only the configuration files need to be updating, making this much easier than changing the code and recompiling.

To support this process the basics of satellite to Earth communication have been presented. Including orbits and how they affect those transmissions, the various kinds of data transmitted, the different hardware and software components of a ground station and the most commonly used protocols in amateur satellite communications.

Once the developed modules have been integrated into *Hummingbird*, the software package will provide missions with an effective software which will, not only allow tracking and controlling the satellite, but generating useful scientific data and monitoring the results automatically.

Chapter 8

Future work

This chapter describes the next steps to be taken towards full integration of the two modules developed in this work with the rest of the system. The process is described here. The future work will be carried out by the author and also by the ESTCube-1 team.

Unit testing
Even though the software has been fully tested by the author it is intended to also implement unit tests to cover every possible scenario. This will be done with two different tools:

- JUnit[37]
- Mockito[38]

Test the integration with ESTCube-1's development build
The Apache Camel code for the modules to be connected with the rest of the system has already been implemented. However, there have been no tests involving the whole system with the two modules working. This work should be carried out before going on any further.

Integrate with ESTCube-1's live build and with Hummingbird
After the modules have been fully tested in the development environment and have been approved by the people responsible of ESTCube-1's ground segment development they should be integrated into the live build, where they will work with real parameters received from ESTCube-1. In addition, it should also be integrated into Hummingbird when the people in charge of the project consider it convenient.

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